SPECIAL REPORT 92-24

Geology and Geohydrology at CRREL, Hanover, New Hampshire

Relationship to Subsurface Contamination

Sally A. Shoop and Lawrence W. Gatto

November 1992

Abstract

Trichloroethylene (TCE) was discovered in three of the industrial wells at CRREL, as well as in two domestic wells in bedrock across the river. This report describes the geohydrology of the CRREL vicinity and the subsurface behavior of TCE as part of the preliminary assessment of the CRREL site. There are three hydrologic units near CRREL—a high permeability esker deposit, lower permeability lake sediments and fractured bedrock. The esker is a high-yield sand aquifer paralleling the river that provides industrial water to CRREL from four wells. The pumping of these wells may induce groundwater recharge from the river. The lake deposits consist of fine-grained silt and sand with some clay, and these cover the esker deposit. These sediments lie above the fractured, folded and metamorphosed volcanics (schist and phyllite) of the Orfordville formation. The free surface water table shows very little hydraulic gradient and appears to be continuous through these units, indicating that they are hydraulically connected. TCE can migrate in the vapor phase, as a soluble component moving along with the groundwater, and as a separate or free phase. Small spills of TCE in the fine-grained soils at CRREL may not have exceeded the retention capacity of the soils and may remain within the soil pores, with a soluble component reaching the groundwater through infiltration. Larger spills may have passed through the saturated soil zone seeking bedrock lows, continuing their downward movement along bedrock fractures. Since the CRREL wells may induce recharge from the river, the possibility of the contamination coming from that direction should not be overlooked.

Cover: View of the esker just north of CRREL.

For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, *Metric Practice Guide,* published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

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U.S. Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

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PREFACE

This report was prepared by Sally A. Shoop, Research Civil Engineer, Applied Research Branch, Experimental Engineering Division, and Lawrence W. Gatto, Geologist, Geological Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory.

Technical review of this report was provided by Dr. Daniel E. Lawson and Paul V. Sellmann, both of CRREL.

The authors thank Lawrence Perry, Robert Northam, David Gaskin and Robert Sletten of CRREL for their generous assistance in collecting data and information, and John Lyons of Dartmouth College and John Cotten and Sara Flanagan of the USGS for discussions on the geology and geohydrology of the area. They are also indebted to Mark Hardenberg, Matthew Pacillo, Edward Perkins and Donna Valliere for their efforts in editing, drafting the figures, and assembling the report.

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These conversion factors include all the significant digits given in the conversion tables in the ASTM *Metric Practice Guide* (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	*By*	*To obtain*
inch	25.4	millimeter
foot	0.3048	meter
$foot^2$	0.0929304	$meter^2$
$foot^3$/second	0.02831685	$meter^3$/second
mile	1609.347	meter
$mile^2$	2589998.0	$meter^2$
pint	0.0004731765	$meter^3$
gallon/minute	0.00006309020	$meter^3$/second
gallon/day	0.00000004381264	$meter^3$/second

Geology and Geohydrology at CRREL, Hanover, New Hampshire
Relationship to Subsurface Contamination

SALLY A. SHOOP AND LAWRENCE W. GATTO

BACKGROUND

Trichloroethylene (TCE) was initially discovered in three of the CRREL groundwater wells in November 1990. Shortly afterward, other sites at CRREL and nearby water wells were tested; TCE was detected in soils at CRREL and in two residential water supply wells across the river. TCE was used as a refrigerant at CRREL from 1960 to 1987, as described by Faran (1991). The resulting chemical analysis program initiated by CRREL and the results from well sampling at the CRREL site, along with the well sampling program for CRREL neighbors (any wells within a few miles of CRREL), are discussed by Perry (1991) and Ecology and Environment (in press).

This report synthesizes information on the geology and groundwater conditions around CRREL and describes the behavior of TCE in a groundwater environment. It was completed as a preliminary site assessment to be used in current and future studies of the geohydrology and the movement of groundwater and contaminants at CRREL.

GEOLOGY

Topography

CRREL is located in the Connecticut River valley on a stepped terrace about 120–130 ft above the river, 1.7 miles north of Hanover, New Hampshire (Fig. 1). When the TCE contamination was discovered in the Vermont wells, CRREL decided to compile all available geologic and geohydrologic information for the area within 1 mile of CRREL, with the most emphasis placed on the area within 0.5 miles. Figure 2 is a map of the CRREL site showing the location of CRREL wells and borings (as of the fall of 1991).

The aerial photographs in Figure 3 document local land use changes from 1966 to 1978; additional photographs are available at CRREL (App. A). As shown in Figure 4, land use in the area is primarily deciduous and mixed forest land (labeled 41 and 43 on map) with fewer areas of residential development (11) and scattered zones of cropland–pasture (21), commercial–services (12) and industrial (13).

The Connecticut River valley, entrenched in a bedrock channel cut into complex, crystalline rock, varies greatly in width and has steep, abrupt walls (Stewart and MacClintock 1969). The shape of the valley varies partially because of bedrock hardness, which influenced the effectiveness of erosion by glaciers and the river. General regional topography and local topography near CRREL has rounded upland profiles, rolling hills, river valley terraces, numerous lakes, ponds and swamps, and stony and sandy subsoil (Hadley 1950). The existing topography and drainage are a direct result of the last 60 million years of erosion, glacial erosion and deposition, and post-glacial eustatic rebound, with concurrent fluvial erosion and mass-wasting processes continually modifying the landscape (Lyons 1958).

Geomorphology and sediments

Glaciers covered the CRREL area twice during the Late Wisconsin period (about 25,000–10,000 years ago). For the most part, evidence for pre-Wisconsin glaciations has been obliterated by the Wisconsin glaciers, although such glaciations probably occurred (Stewart 1961, Stewart and MacClintock 1969). During the first (oldest) Wisconsin glacial advance, named the Bennington Glacial

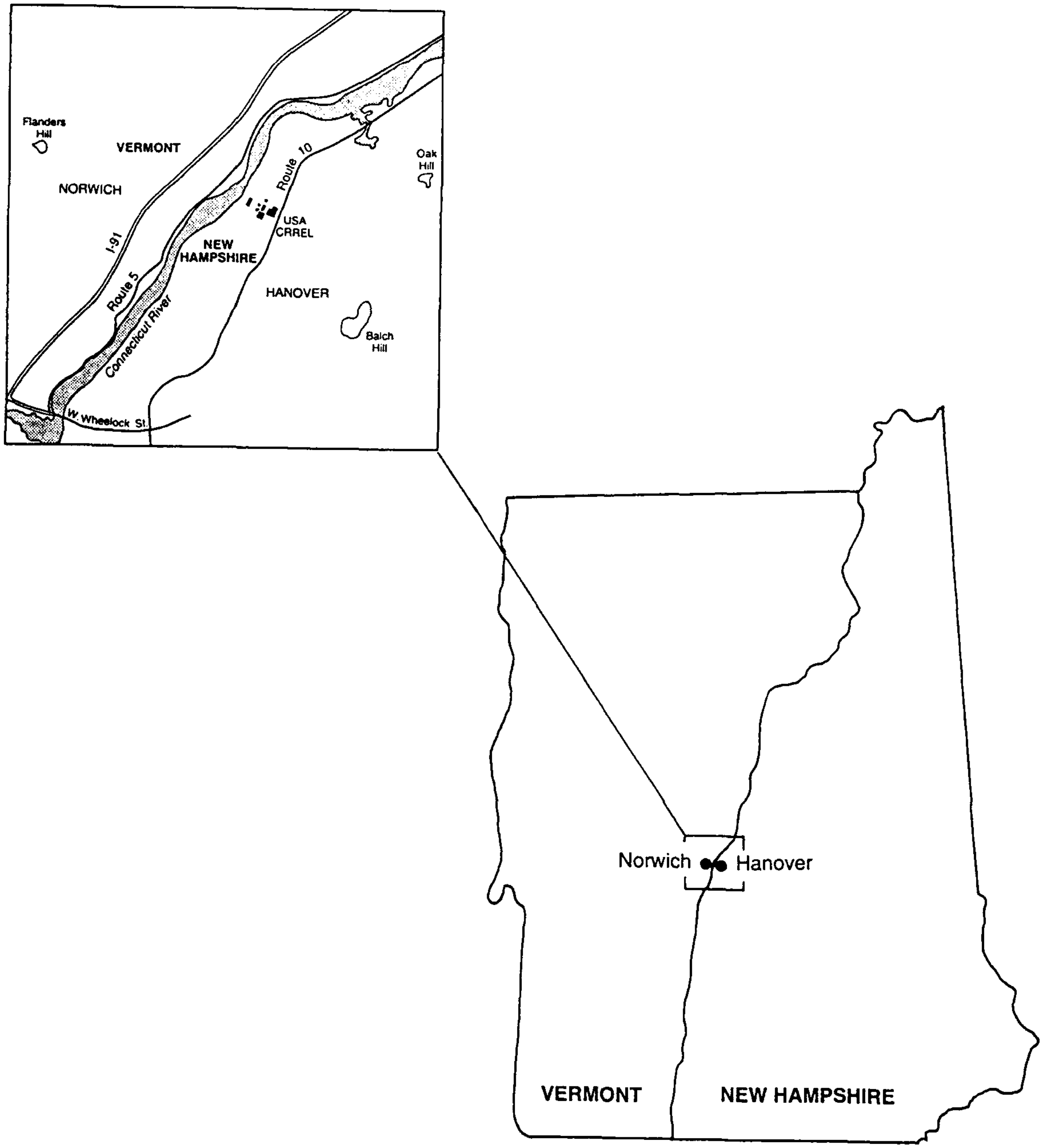


Figure 1. Location of U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Stade in Vermont, glaciers advanced primarily from the northwest. When they receded, a glacial lake formed in the Connecticut River valley (Stewart and MacClintock 1969). Approximately 20,000 years ago, during the Shelburne Glacial Stade, glaciers readvanced, moving essentially down the Connecticut River valley from the northeast (Fig. 5).

During the Bennington and Shelburne stades, the glaciers were about a mile thick, and they steepened and deepened the Connecticut River valley into a classic U-shape, depositing two general types of sediment: thin till, usually found in upland areas over bedrock, and glaciofluvial kames, kame terraces and eskers along valleys (Fig. 6). The youngest till left by the Shelburne-age glacier is primarily a loose, sandy ablation till with a few areas of dense basal till. Physical properties of the tills in New Hampshire are summarized by Goldthwait (1948b) but will not be addressed here because they do not occur on the CRREL property.

About 13,000 to 11,000 years ago, the Shel-

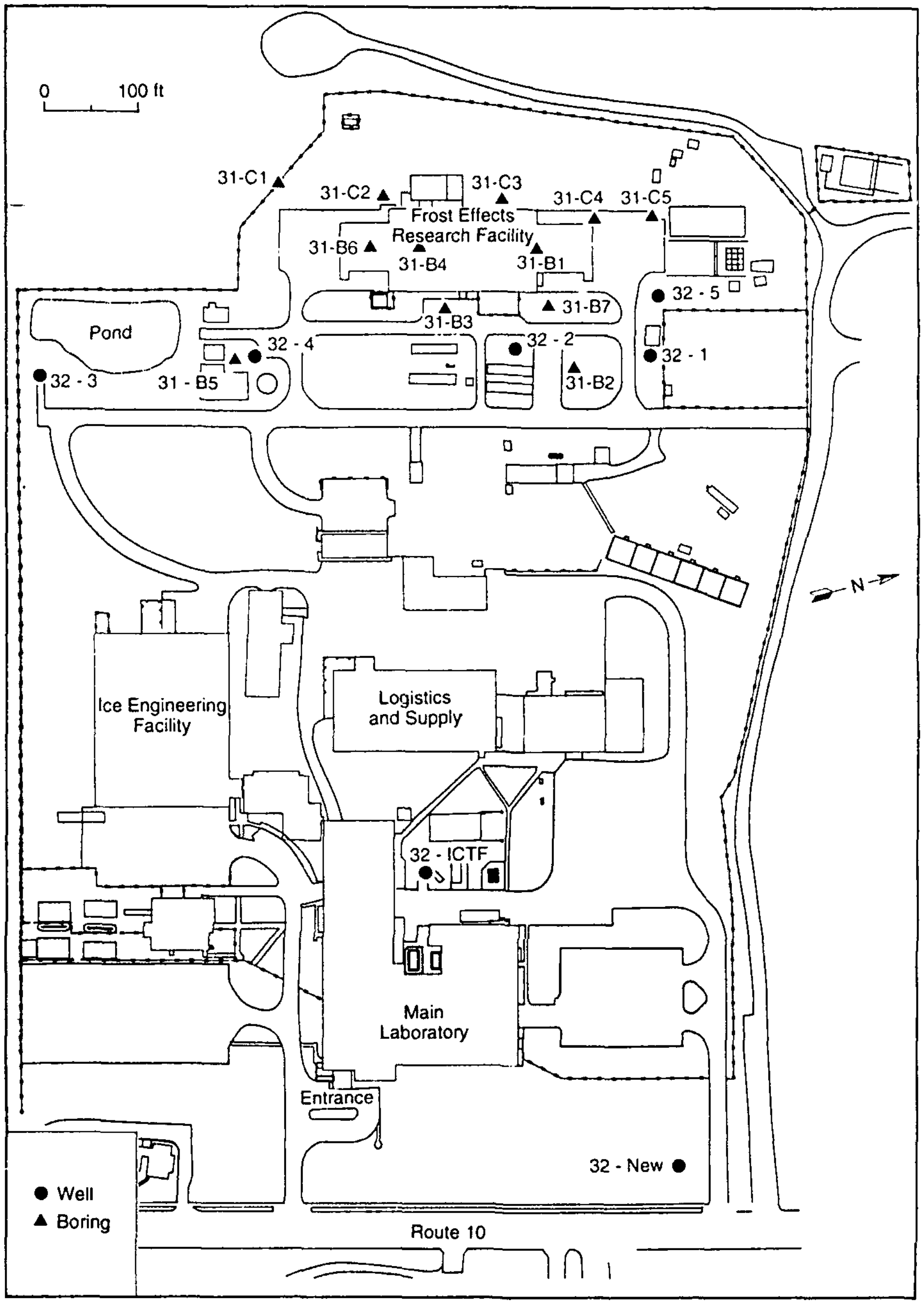


Figure 2. CRREL site showing locations of wells and borings (as of fall 1991).

burne-age glaciers retreated from this area and glacial Lake Hitchcock filled the Connecticut River valley (Fig. 7) when the valley was dammed by a glacial moraine near Middletown, Connecticut (Lyons 1958, Stewart 1961, Stewart and MacClintock 1969). This Lake Hitchcock Interstade lasted at least 2300 years (Stewart and MacClintock 1969) and possibly 4100 years (Stewart 1961). The level of Lake Hitchcock in the CRREL area has been estimated at about 650–700 ft above mean sea level (msl), based on the level of lacustrine sediments along valley walls (Elston and Washburn 1954, Lyons 1958, Stewart and MacClintock 1969). Hanover rests on a plain of these lacustrine sediments (Lyons 1958).

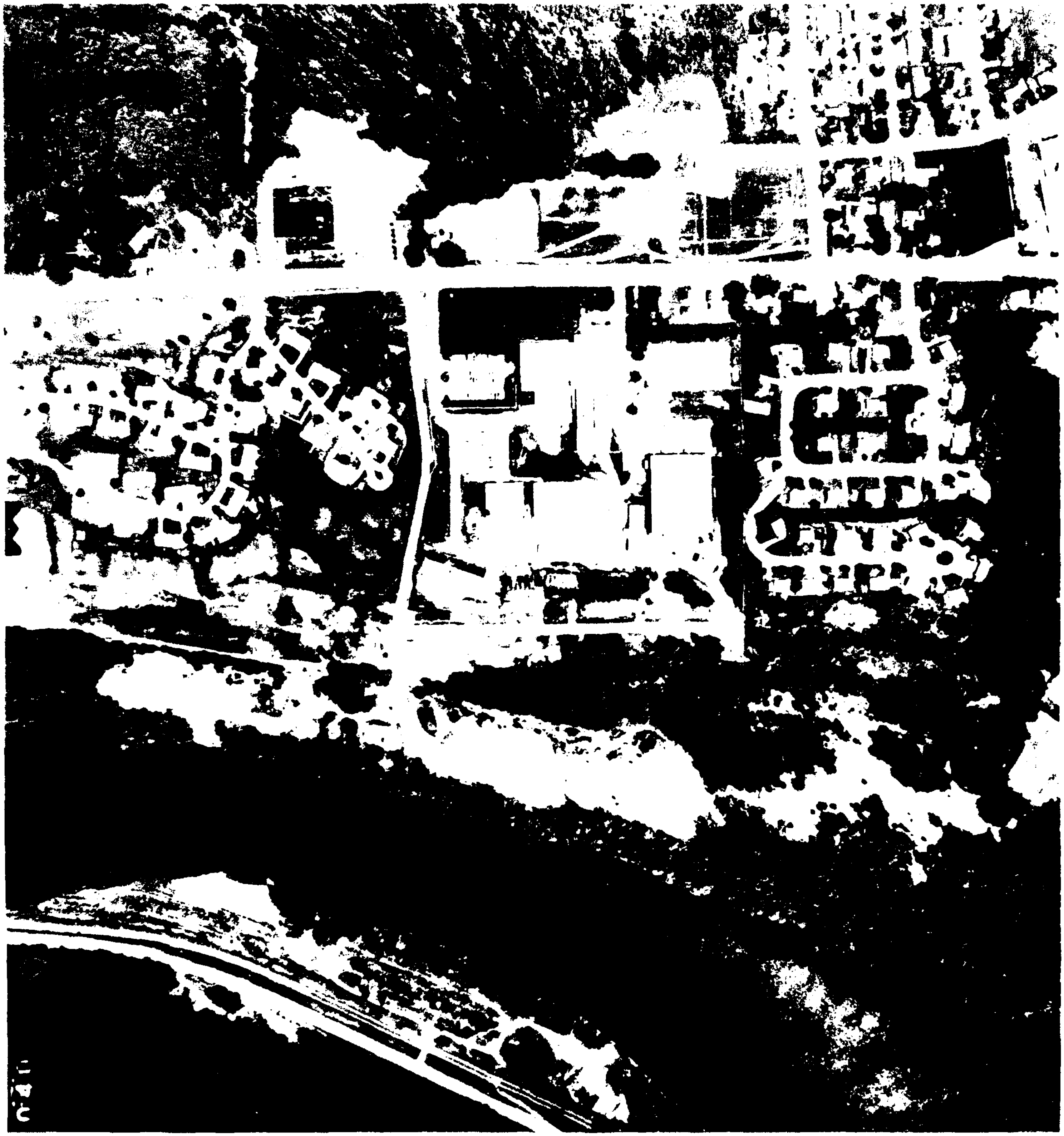
The presence of tills on varved clays in scattered locations suggests that there was a glacial readvance after the Lake Hitchcock Interstade; this was followed by a new, smaller glacial lake phase, Lake Upham, although no firm evidence exists for this (Stewart and MacClintock 1969). Lake Upham may simply be a later phase of Lake Hitchcock

a. 9 October 1966 (1:17,000).

Figure 3. Aerial photos of the CRREL area.

b. 4 September 1975 (1:5000).

Figure 3 (cont'd).



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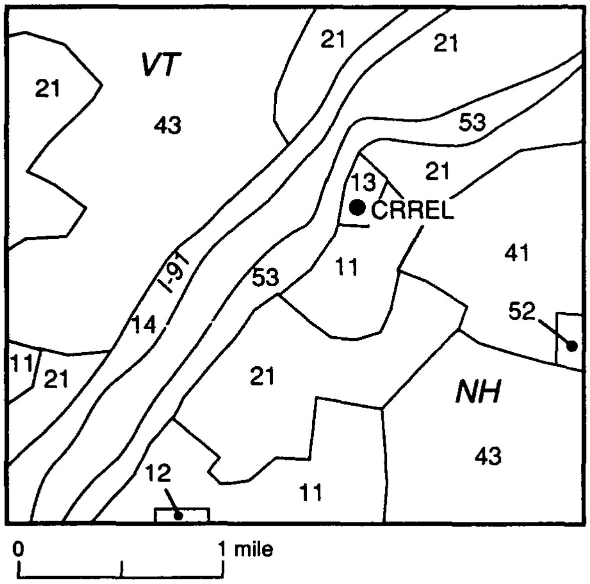


Figure 4. Land uses in the CRREL–Hanover area (after USGS 1972)—11 = residential; 12 = commercial and services; 13 = industrial; 14 = transportation, communication and utilities; 21 = cropland and pasture; 41 = deciduous forest land; 43 = mixed forest land; 52 = lakes; 53 = reservoir.

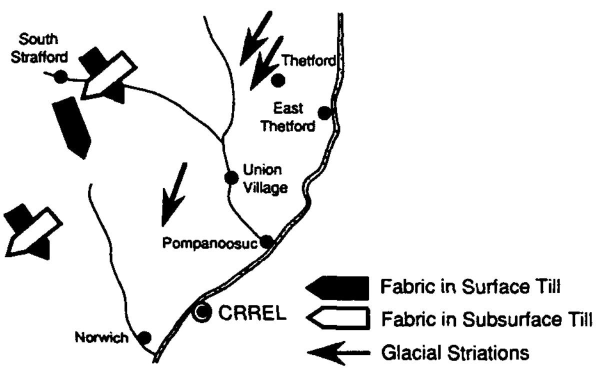
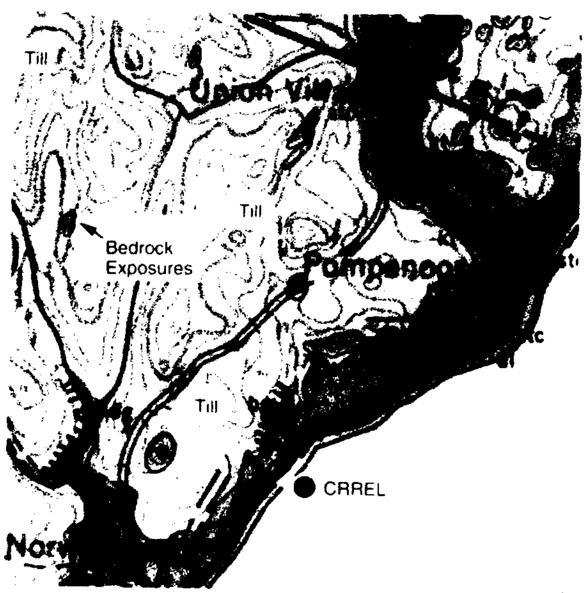


Figure 5. Drift sheets and ice directions in the Shelburne Drift in Vermont (after Stewart and MacClintock 1970).



t = glacial till mantling the bedrock and reflecting the topography of the underlying bedrock surface; thicker in the valleys and thinner in the uplands; on many exposed uplands postglacial erosion has left only rubble and scattered boulders on the bedrock.
stc = glaciolacustrine lake-bottom sediments, silt, silty clay, clay.
bg = glaciolacustrine littoral sediment predominantly gravel and beach gravels.
ls = glaciolacustrine littoral sediment predominantly sand; well-sorted sand, no pebbles or boulders.
al = post-glacial fluvial recent alluvium; fluvial sands and gravels.
km = glaciofluvial kame gravel; ice-contact outwash gravel, kame moraine, kame complex with morainic topography.

Figure 6. Surficial geology in Vermont near CRREL (after Stewart and MacClintock 1970).

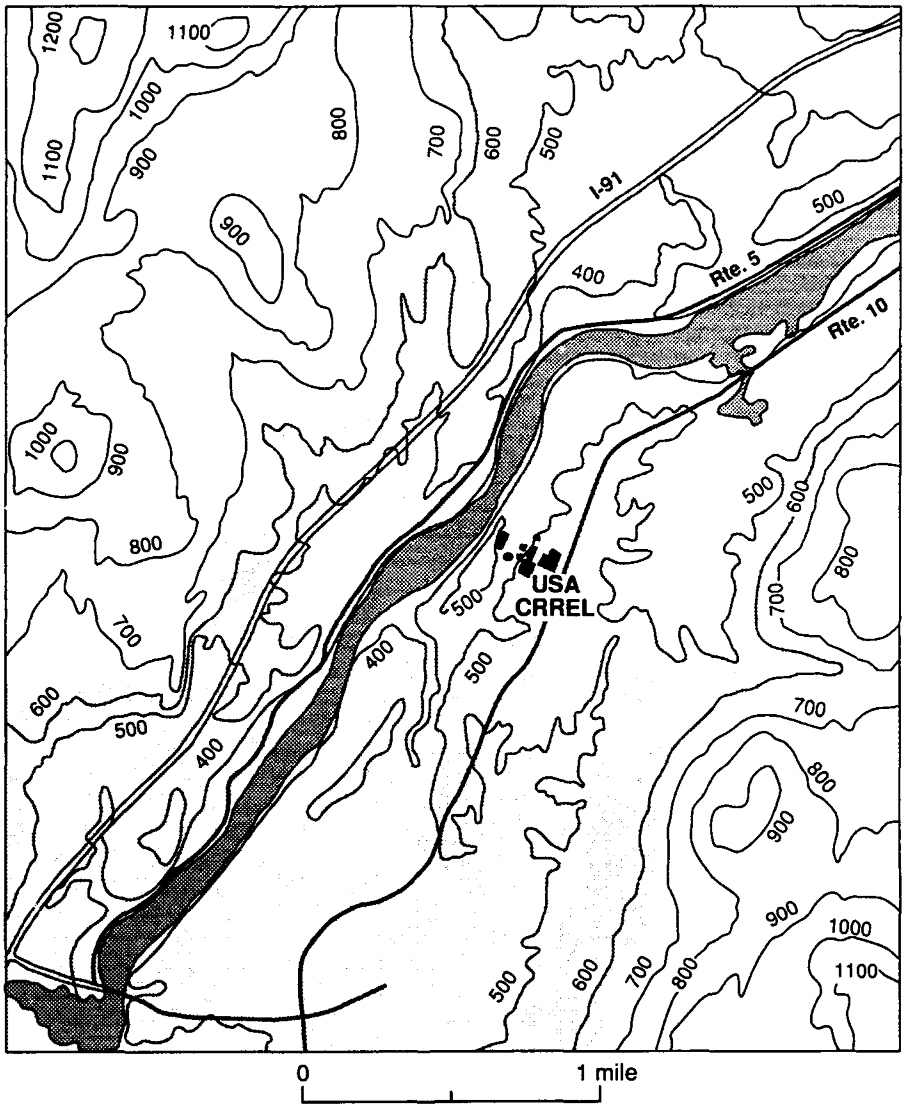


Figure 7. Maximum extent of glacial lakes in the Hanover area (after Stewart and MacClintock 1970). The water level was at 650–700 ft above msl and the lake floor was at 500–540 ft above msl.

after the natural dam across the Connecticut River valley in Connecticut broke and the water level fell some 90 ft to 560–610 ft above msl (Stewart 1961).

The glacial sediments in the Connecticut River valley surrounding CRREL are predominantly kame gravels, variable esker deposits and lacustrine sediments, including varved clays, laminated silts and clays, sand, pebbly sand, gravels and deltaic deposits. The mineral content of the sands is variable, with a sample from Sand Hill in Hanover (west side of Rt. 120 near the Hanover–Lebanon town line) showing 56% quartz, 1% feldspar, 8% mica, 28% slate and 7% quartzite (Goldthwait 1948a). Most of the valley lacustrine deposits usually extend to bedrock because till and outwash are generally lacking below them (Hadley 1950, Stewart and MacClintock 1969). The sediment logs from the wells drilled on CRREL property indicate that tills do not underlie the on-site stratified sediments, which are predominantly lacustrine deposits.

Stewart and MacClintock (1969) report that the so-called esker that runs along the east side of the river on the CRREL property and crosses the river to the north (Fig. 8) is actually a ridge of kame gravel and is not continuous like a classic esker. Lyons* is convinced it is an esker and not a kame

*Personal communication with J. Lyons, Dartmouth College, 1991.

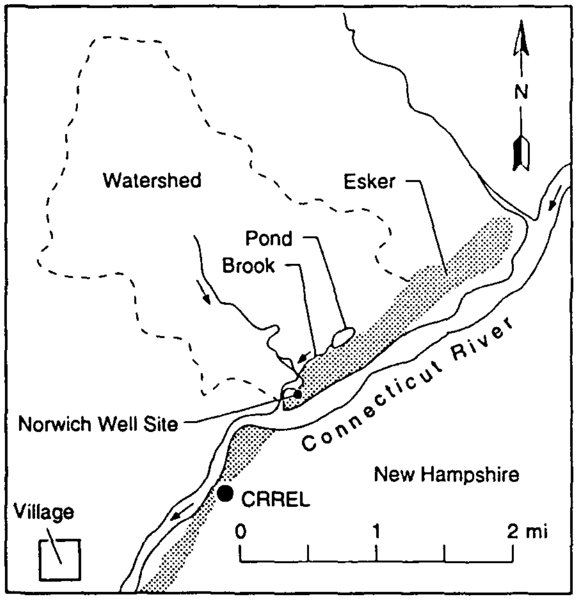


Figure 8. Approximate location of the esker (after Caswell 1990).

because of its location at the center of the valley, an area not expected to be an ice margin. In either case, it is considered older than Lake Hitchcock sediments since it is partially buried by the lake sediments (Fig. 9). The sediment thickness over the bedrock canyon cut by the Connecticut River before glaciation varies from 50–60 ft over much of the valley (Hadley 1950), is locally 4 to 200 ft (Lyons 1958, Stewart 1961, Stewart and MacClintock 1969) and is about 170 ft at CRREL, as shown in the logs of the CRREL wells in Figure 10. Hodges et al. (1976) report thicknesses of the unconsolidated deposits in the region varying from 0 to 120 ft.

A summary of the boring logs within approximately 1 mile of CRREL is presented in Table 1; the locations of the borings are shown on Figure 11. The depths of wells and bore holes vary as follows: 18 are equal to or less than 100 ft deep, 23 are 101–200 ft, seven are 201–300 ft, three are 301–400 ft, two are 401–500 ft, one is 501–600 ft, and four are 601–700 ft. Twenty-eight are known to have hit bedrock and the depths to bedrock varied from 4 to 200 ft.

The 53 well and boring logs listed in Table 1 show the variability in sediment type and thickness in the CRREL area. Their accuracy depends on the sample type and on the well logger's ability to identify sediment types; therefore, some of the variability can be attributed to the logging and sampling procedures used in the field. The logs of these 53 borings are given in Appendix B.

Soils developed in the upper 5 to 6 ft of the sediments within 1 mile of CRREL are listed in Table 2 and their distribution is shown in Figure 12. The soil within the immediate vicinity of CRREL is the Hitchcock silt loam, a deep, well-drained soil in silty lacustrine material. Detailed characteristics

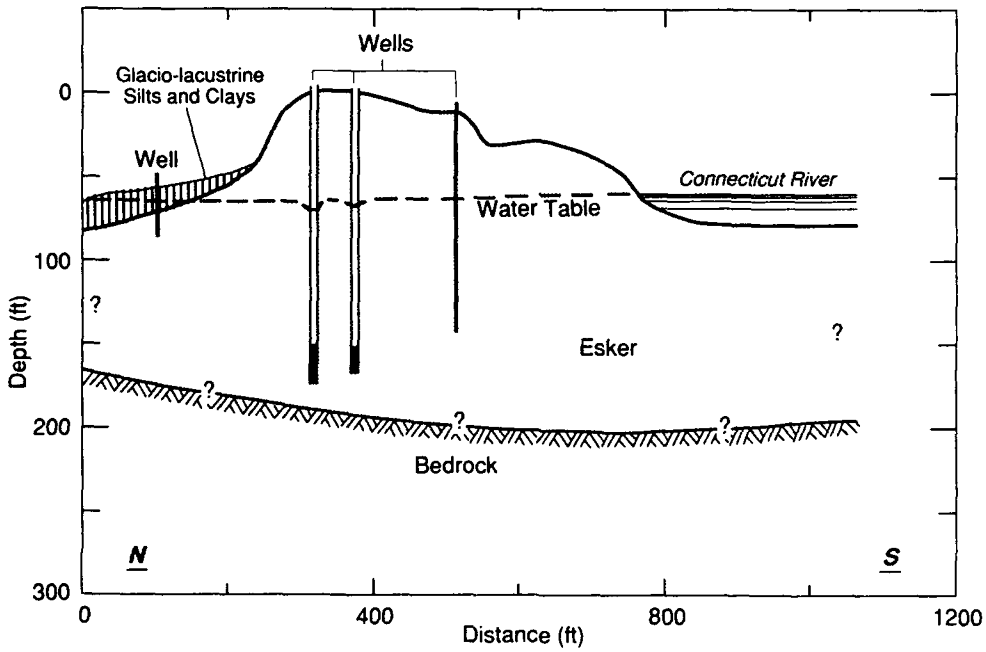


Figure 9. Esker partially buried by lacustrine silts and clays of the Norwich well field (after Caswell 1990).

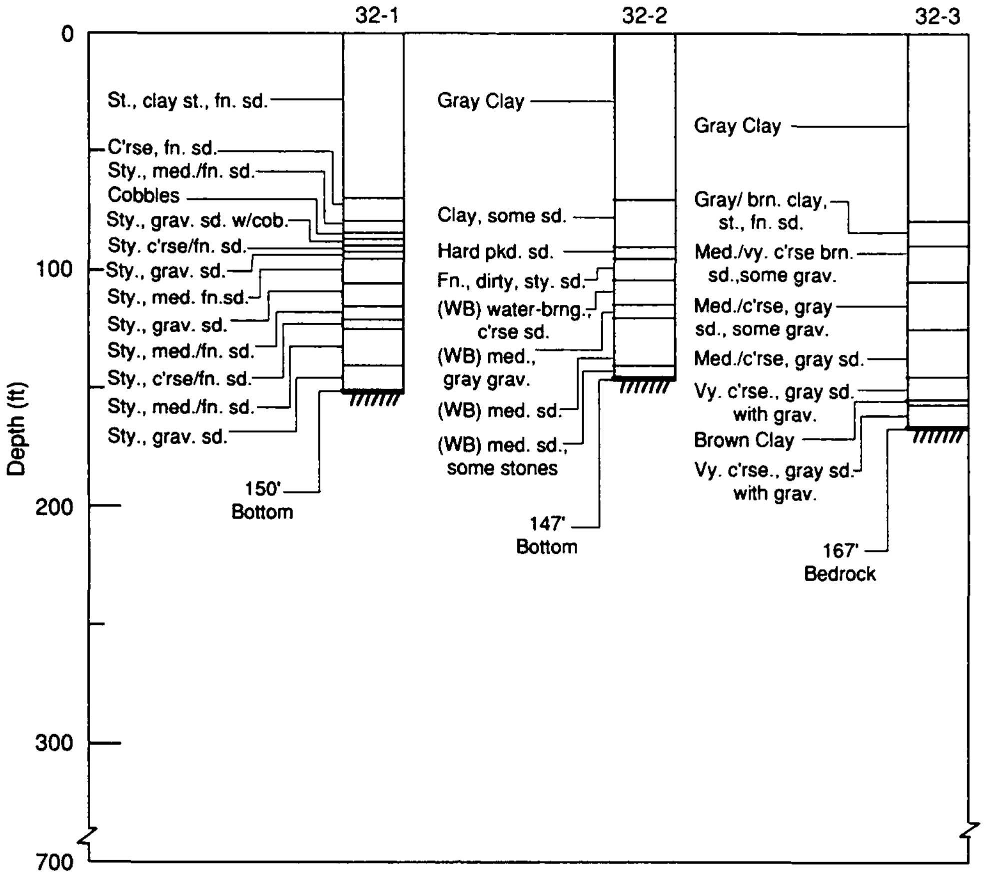


Figure 10. Stratigraphy of CRREL industrial water wells.

Table 1. Information on wells within about 1 mile of CRREL (references from which data are taken are listed at the end of the table).

*Well no.**	*Depth to bedrock (ft)*	*Total depth (ft)*	*Yield (gal./min)/aquifer*	*Sediment log available*	*Where screened (ft)*	*Well head elevation (ft)*	*Depth to water when drilling (ft)*	*Static water level (ft)*
1	unk†	63	125/sg	no	np†	np†	np†	np†
2-1	unk	63	125+/np	no	np	np	np	np
2-2	unk	150	322/np	no	np	np	np	np
3-1	unk	154	500/np	no	np	np	np	np
3-2,3,4 (wf)	unk	150	1500 (wf)/np	no	np	np	np	np
7-B3	unk	61	nnw	yes	np	np	nw	nw
7-B4	unk	51	nnw	yes	0–25	np	nw	nw
7-B5	unk	41	nww	yes	0–20	np	nw	nw
8	170–190 (estimated)	170	300+/np	gen'l x-section	150–170	np	np	np
9-Britton well	126	355	10/np	no	np	np	np	50
9-195	74	340	2/bx	yes	np	np	np	np
9-50	34	605	0.375/bx	yes	np	np	np	np
9-96	68	265	13/unc	yes	np	np	np	30
9-190	unk	85	np/grav	yes	80–85	np	np	np
9-323	4	160	6/bx	yes	np	np	np	np
9-243	60	465	3/bx	yes	np	np	465	np
9-91	7	545	3/bx	yes	np	np	525	35
9-324	18	300	2/bx	yes	np	np	160 –275	14
9-62 (4-41)	30	383	0.5/np	yes	np	np	90	40
9-152 (11-8-in. existing)	unk	170	200/unc	yes	155–170	np	np	62.25
9-394 (11-7A)	unk	191	747/unc	yes	155–175	np	np	67.21
9-393 (11-1)	unk	35	20/unc	yes	25–30	np	np	9
9-392 (11-2)	unk	115	np/np	yes	109–114	np	np	50
9-388 (11-5)	unk	153	np/np	yes	116–126	np	np	45.75
9-390 (11-6)	unk	120	np/np	yes	91–101	np	np	42.70
9-391 (11-7)	unk	161	20/np	yes	155–160	np	np	67.90

Table 1 (cont'd)

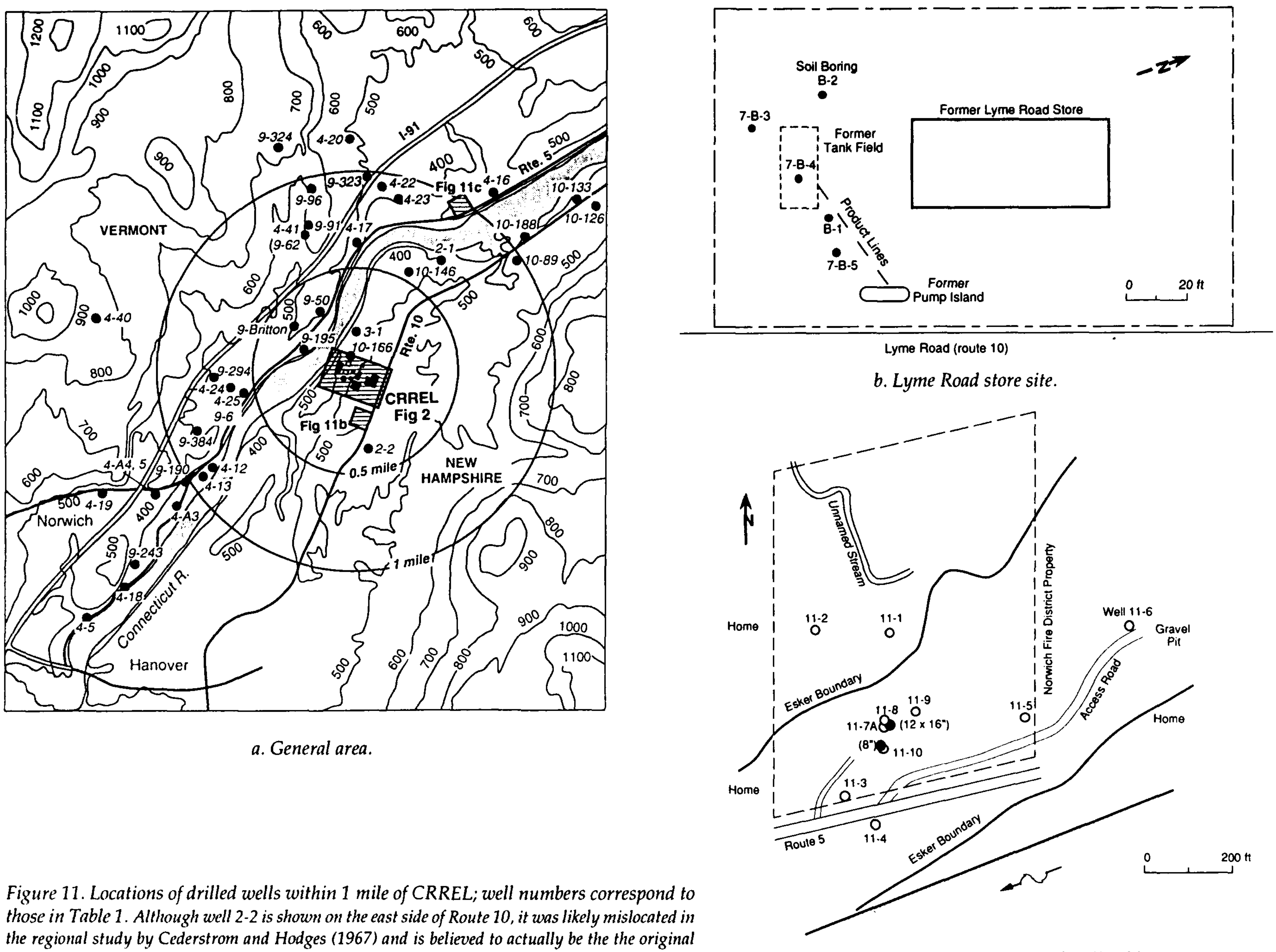
Well no.*	Depth to bedrock (ft)	Total depth (ft)	Yield (gal./min)/aquifer	Sediment log available	Where screened (ft)	Well head elevation (ft)	Depth to water when drilling (ft)	Static water level (ft)
9-384	25	690	4/bx	yes	np	np	np	70
9-294	109	440	2.5/bx	yes	np	np	np	np
9-6 (4-25)	21	260	15/bx	yes	np	420	np	np
9-39 (11-3)	unk	156.25	614/unc	yes	114–134	np	np	48
10-166	162	160	366/unc	yes	125–160	460	145	91
10-146	unk	32	nww	yes	nww	460	np	np
10-188	unk	110	60/unc	yes	np	400	np	25
10-89	27	280	8/bx	yes	np	420	np	np
10-133	85	220	20/bx	yes	np	420	np	np
10-126	110	300	20/bx	yes	np	440	np	np
11-8″	unk	135	np/np	yes	114 –134	np	np	48
11-8	unk	150	5/unc	yes	145–150	np	np	66
11-9	unk	150	5/unc	yes	145–150	np	np	66.3
11-5A	unk	131	12/unc	yes	126–131	np	np	54.3
4-A3	unk	130	nww	yes	np	390	np	np
4-A4	unk	35	nww	yes	np	410	np	np
4-A5	unk	40	nww	yes	np	410	np	np
4-5	18	127	3/bx	no	X	400	np	5
4-12	30	200	4/bx	no	X	400	np	np
4-13	30	75	25/bx	no	X	390	np	np
4-16	unk	30	5/gravel	no	o	410	np	20
4-17	40	297	0.5/bx	no	X	430	np	40
4-18	unk	18	np/sand	no	o	390	np	15
4-19	unk	90	10/unc	no	o	470	np	np
4-20	unk	207	5/unc	no	X	530	np	np
4-22	70	262	50/bx**	no	X	430	np	np
4-23	200	601	15/bx	no	X	430	np	np
4-24	21	625	3/bx ††	no	X	480	np	100
4-25 (9-6)	21	260	15/bx **	yes	X	420	np	np
4-36	unk	134	6.14/sdy. grav.	yes	yes ***	430	np	51
4-37	unk	129	np/sdy. grav.	yes	yes ***	430	np	51
4-40	unk	240	100/unc	no	X	870	np	np
4-41 (9-62)	30	383	0.5/bx	yes	X	600	np	40
31-B1	ne	90	0/unc	yes	ns	499	ne	nw
31-B2	ne	60	0/unc	yes	ns	465	ne	nw
31-B3	ne	49.25	0/unc	yes	ns	462	3 (perched)	nw
31-B4	ne	80	0/unc	yes	ns	492	ne	nw
31-B5	170.7	171.7	0/unc/bx	yes	ns	462 3 (perched)	90–92	14
31-B6	ne	36.5	0/unc	yes	ns	np	ne	np
31-B7	ne	41.5	0/unc	yes	ns	np	np	np
31-C1	ne	21.5	0/unc	yes	ns	np	np	np
31-C2	ne	24.5	0/unc	yes	ns	np	np	np
31-C3	ne	21.5	0/unc	yes	ns	np	np	np
31-C4	ne	12.5	0/unc	yes	ns	np	np	np
31-C5†††								
32-1 (FD-6[ow])	ne	150	600/sdy. grav.	yes	ns	462.4	np	77.8
32-2	ne	147	300/sdy. grav.	yes	np	462.1	np	np
32-IEF (32-3)	167	167	650/sdy. grav.	yes	110–150	np	np	np
32-Town Hanover (aband.)	ne	150	np	yes	np	np	np	np
32-4	np	150	130/sdy. grav.	no	np	np	np	np
32-5	np	np	np	no	np	np	np	np
32-ITCF	np	200	nww	no	ns	np	np	np
32-FD-1 to FD-5	np	np	np	no	np	np	np	np
32-new (see Appendix G)								

* Wells are designated by a reference number first and a second number if the reference deals with more than one well. Wells with two sets of numbers in a column, one set in parentheses, are the same wells referenced in two sources.

1. Hodges and Butterfield (1968)
2. Cederstrom and Hodges (1967)
3. Cotton (1976)
4. Hodges et al. (1976)
7. *Groundwater Technology* (1989)
8. Caswell (1990)
9. Young (1990)
10. Schofield (1990)
11. Winkley and Caswell (1990)
29. Perry (1991)
31. CRREL (1980)
32. CRREL (undated)

** Coarse-grained, metamorphic gneiss, quartzite, marble
†† Fine-grained schist, slate
*** Depth range not provided
††† No log available.

† Legend:
unk – unknown
np – information not provided
nww – not a water well
nw – no water
wf – well field
sg – sand and gravel
bx – bedrock
ow – old well
grav – gravel
o – open end
X – open hole in aquifer (usually cased to aquifier)
ns – not screened
ne – not encountered
p – personal communication
IEF – Ice Engineering Facility
ICTF – Ice Core Testing Facility (well for research drilling techniques in ice; constructed in 1964)



a. General area.

b. Lyme Road store site.

c. Norwich, Vermont, municipal well field.

Figure 11. Locations of drilled wells within 1 mile of CRREL; well numbers correspond to those in Table 1. Although well 2-2 is shown on the east side of Route 10, it was likely mislocated in the regional study by Cederstrom and Hodges (1967) and is believed to actually be the the original CRREL well, 32-1, in the esker.

Table 2. Soils within one mile of CRREL (see Fig. 12).

New Hampshire (Soil Conservation Service 1988)	*Vermont* (Soil Conservation Service, undated)
Rippowam fine sandy loam, 5	Hitchcock silt loam, 1 B,C,D,E (25–50%)
Agawam fine sandy loam, 24 A,B	Belgrade silt, 2A
Windsor loamy fine sand, 26 C,E (15–60%)	Raynham silt, 4A (0–5%)
Hadley silt loam, occasionally flooded, 108	Windsor loamy fine sand, 5A,B (1–8%), C,E (25–60%)
Hitchcock silt loam, 130, A, B, C, E (15–60%)	Hinckley loamy fine sand, 14C
Dartmouth silt loam, 132 B	Vershire–Dummerston complex, 19C (rocky)
Gravel pits, 298	Glover–Vershire complex, 20B,C (3–15%), D (15–35%), E (35–60%)(rocky)
Bernardston silt loam, 331 D (very stony)	Buckland fine sandy loam, 25C
Pittstown loam, 336 C (very stony)	Buckland fine sandy loam, 26B,C,D,E (very stony)
Cardigan–Kearsarge complex, 360 D	Cabot loam, 30 B (0–8%), C, E
Cardigan–Kearsarge–Rock outcrop complex, 361 C,D,E (25–60%)	Markey muck, 47
	Sand and gravel pits, 48

Letters after number designations indicate the following ground surface slopes (%) unless otherwise indicated:

A = 0–3
B = 3–8
C = 8–15
D = 15–25
E = 25–35, generally; 25–60, occasionally

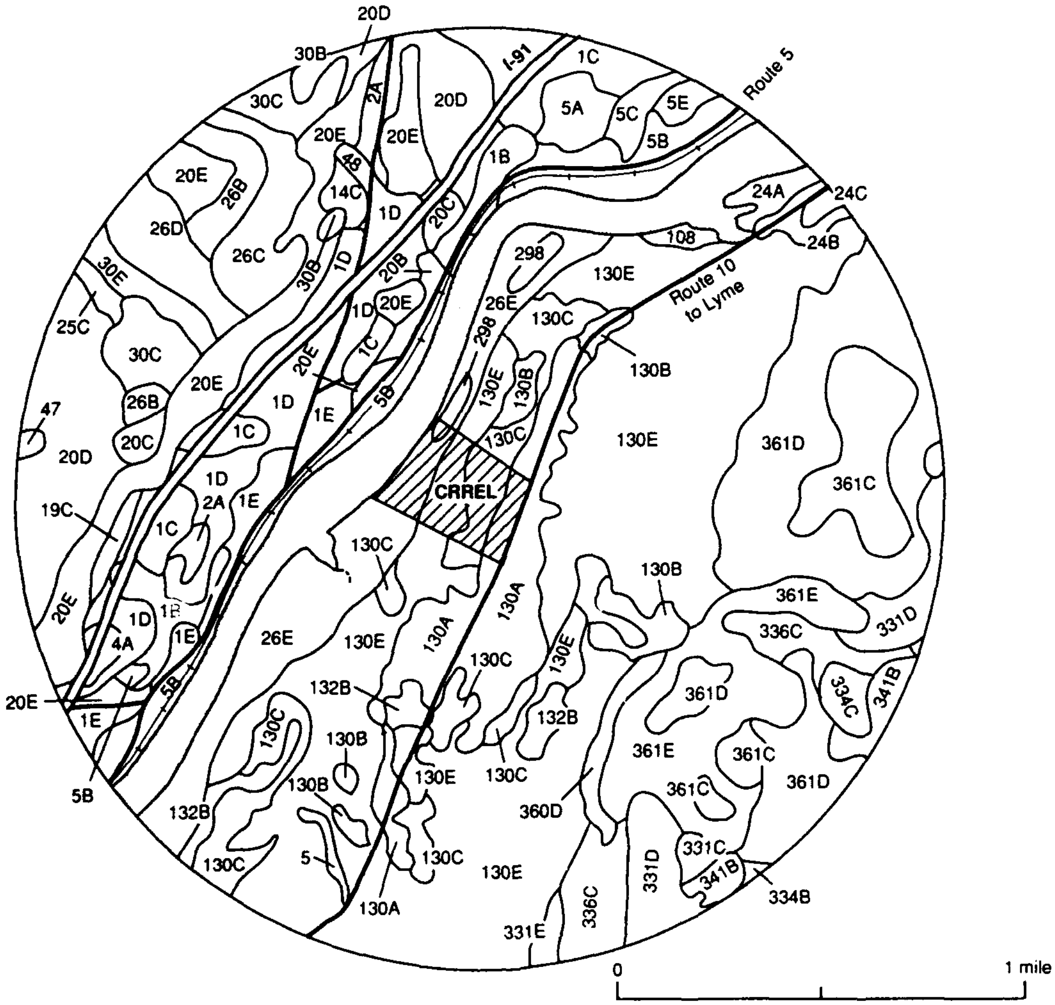
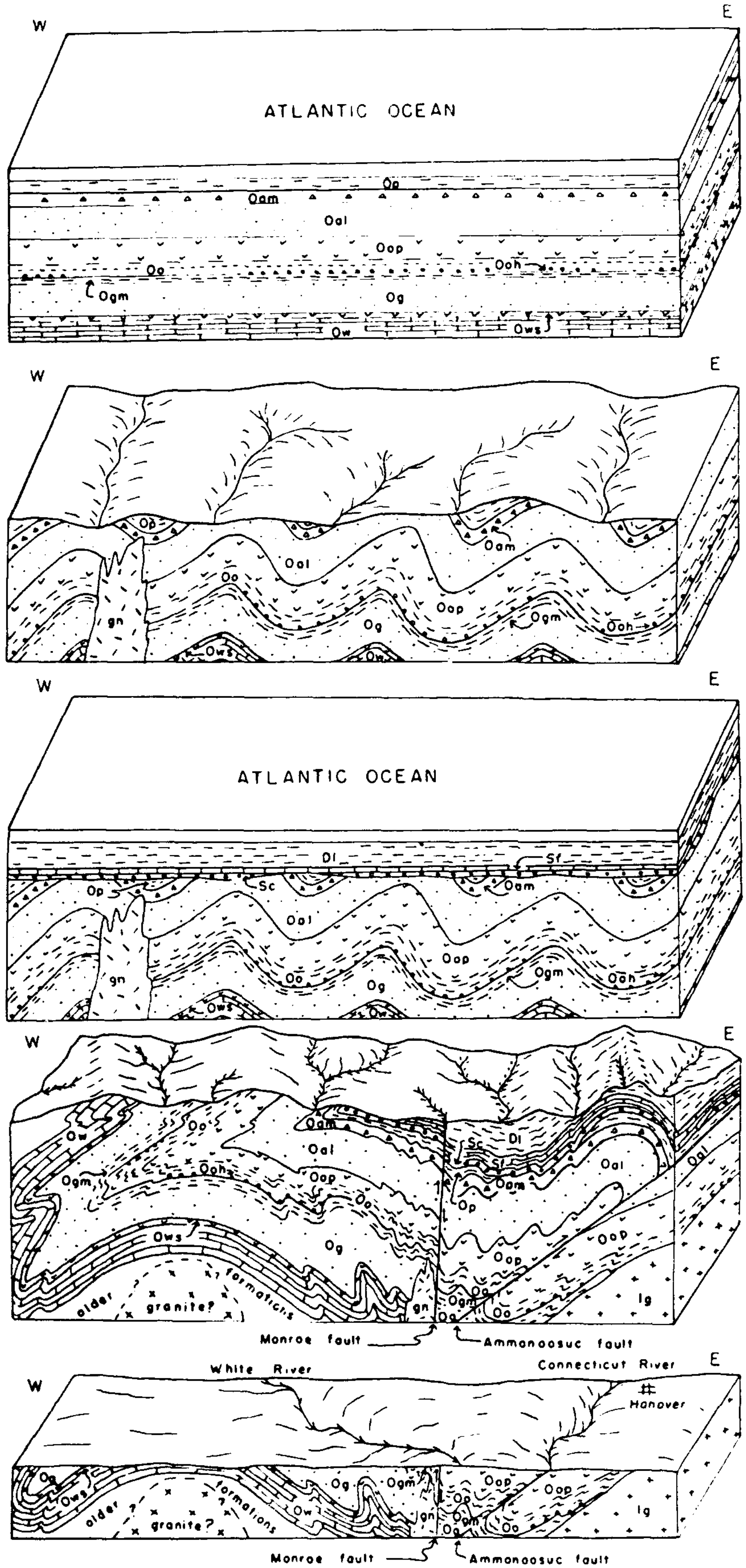


Figure 12. Soils within one mile of CRREL (after maps of the Soil Conservation Service).



a. Upper Valley region toward the close of the Ordovician period (i.e., 400–380 million years ago). **Ow** *is the Waits River formation;* **Ows** *is the Standing Pond amphibolite member of the Waits River formation;* **Og** *is the Gile Mountain formation, and* **Ogm** *is the Meetinghouse member of the Gile Mountain formation;* **Oo** *is the Orfordville formation, and* **Ooh** *is the Hardy Hill member and* **Oop** *is the Post Pond member of the Orfordville formation;* **Oal** *is the Albee formation;* **Oam** *is the Ammonoosuc volcanics;* **Op** *is the Partridge formation.*

b. Upper Valley region in Early Silurian time. Rocks have been folded and elevated, temporarily, above sea level. Granite (**gn**) *has also been intruded into the rocks during the Late Ordovician orogeny (370 million years ago).*

c. Upper Valley region in the Early Devonian time. Region was resubmerged in Middle Silurian time, and has the Clough (**Sc**) *and Fitch* (**Sf**) *formations (Middle Silurian) and Littleton* (**Dl**) *formation (Lower Devonian) deposited upon the older rocks.*

d. Upper Valley region in Late Devonian time. Rocks were folded in the Middle to Late Devonian Acadian orogeny (300 million years ago), intruded by the Lebanon granite (**lg**)*, metamorphosed, and elevated above sea level. Erosion is actively reducing the area.*

e. Upper Valley region at present. Approximately 5 miles of bedrock have been stripped from the area.

Figure 13. Idealized geologic history of the Upper Valley area (from Lyons 1958).

of the Hitchcock soil series are given in Appendix C. The soil characteristics in the upper 5–6 ft of sediment are probably not critical for the understanding of the hydrogeologic setting and groundwater flow conditions in the area. Groundwater flows at greater depths than the soil-development zone, but spills and leaks may occur at or near the surface.

Bedrock

Bedrock in the CRREL area is highly folded, metamorphosed sedimentary and volcanic rocks with minor intrusives (Hadley 1950). In the well logs (App. B) bedrock is described as schist with variable color and structure, brown ledge, shale, gneiss with quartz layers, gray rock, blue granite, hard gray granite with little quartz, gray granite and phyllite of the Orfordville formation. As previously noted, one needs to be cautious regarding the validity of such identifications.

The local geologic history is summarized as follows (Fig. 13): Paleozoic calcareous sediments, followed by arenaceous sediments with volcanics, were deposited from the Cambrian to Ordovician periods (stage 1); the Taconic orogeny occurred (stage 2); Devonian sediments were deposited and subsequently eroded (stage 3); the Acadian orogeny occurred, with large granitic intrusions and accompanying metamorphism (stage 4); the meager geologic record from the close of the Devonian to the present reveals some Mississippian (?) diabase dikes, followed by the Pleistocene glacial erosion and deposition and recent fluvial erosion and deposition (stage 5). The metamorphic facies in the Hanover area (Fig. 14) indicate the direct relationship between the regional pressure–temperature conditions at the time of metamorphism and the upward projection of two masses of hot, low-density rock into the surrounding deformed sediments and volcanics during the Acadian orogeny.

Existing geologic maps (Hadley 1942; White and Jahns 1950; Lyons 1954, 1955, 1958; Lyons et al. 1986) show that the Ordovician (440–360 million years ago) Post Pond volcanic member (Oop) of

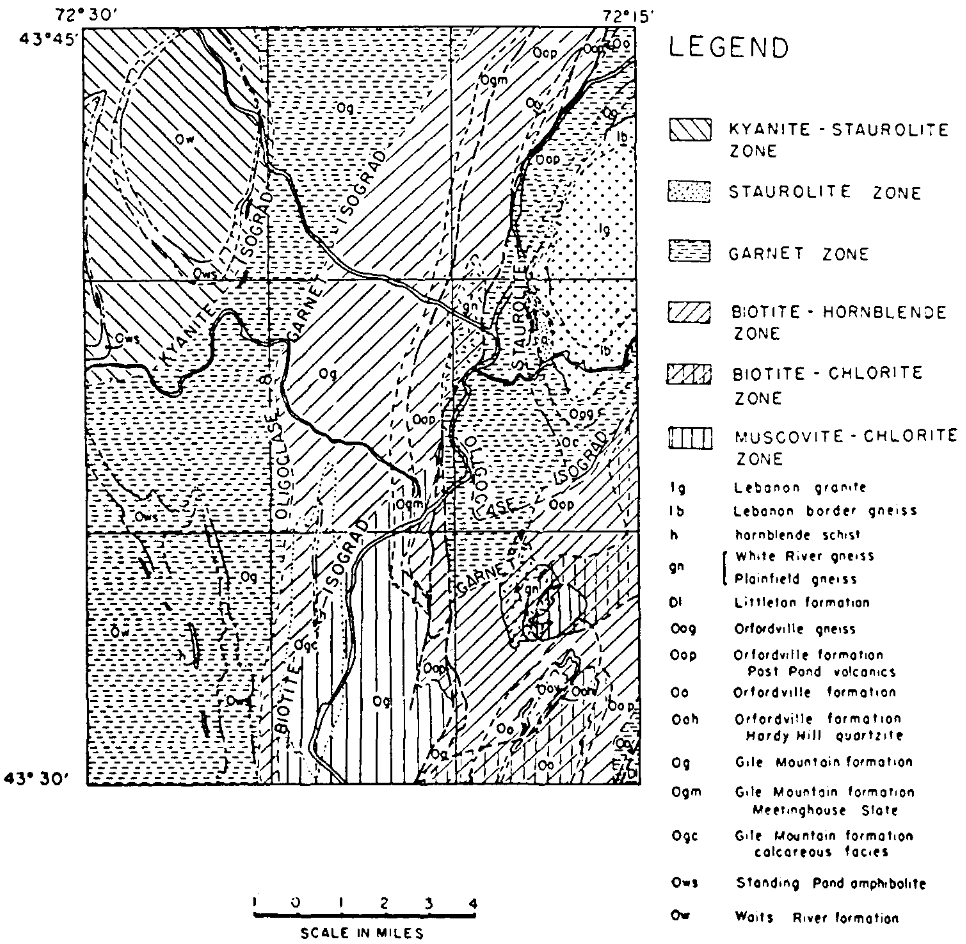
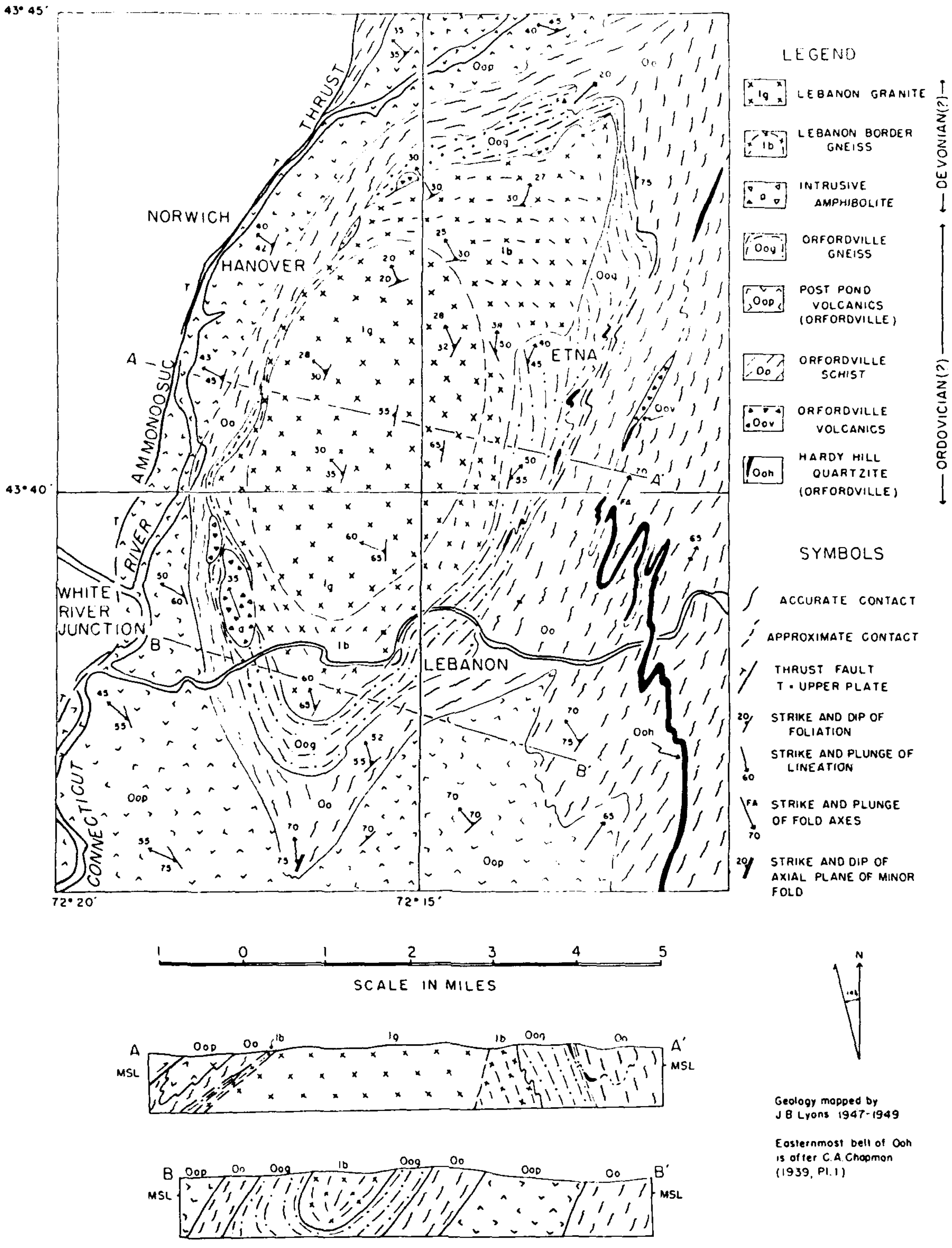
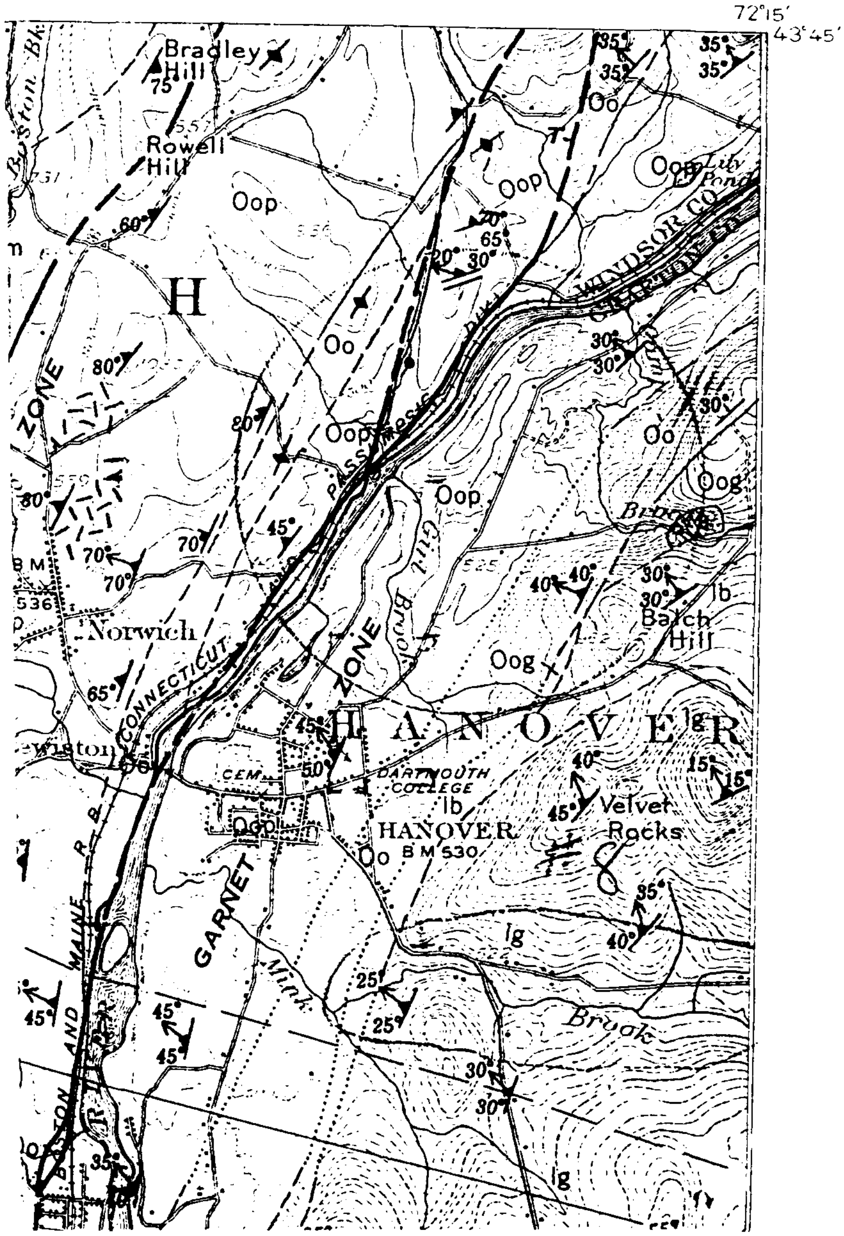


Figure 14. Metamorphic zones of the Upper Valley area (from Lyons 1955).



a. Regional conditions (from Lyons 1955).

Figure 15. Bedrock types, structures and structural trends.



b. Within 1 mile of CRREL, shown by circle (from Lyons 1958).

Figure 15(cont'd).

the Orfordville formation (Oo) underlies the area around CRREL (Fig. 15). This Post Pond member, primarily hornblende schist or chlorite-sericite schist (Lyons 1954, 1958), probably was originally basalt flows that were later reworked with admixtures of sedimentary detritus. Aleinoff (1977) considers the Post Pond member equivalent to the Ammonoosuc volcanics (composed of amphibolite, greenstone and felsic schists with major elements as shown in Appendix D) in the Mt. Cube area to the north.

The Orfordville formation is composed of a variety of rock types, but is predominantly gray, black and tan quartz–mica schist or phyllite with small volcanic lenses (Table 3, Fig. 16). These Orfordville formation metasediments are derived from several thousands of feet of carbonaceous sands and muds, intercalated with primarily basic lavas and tuffs, all of which were deformed and metamorphosed during the Acadian orogeny (Hadley 1950). Lyons* reports that the Orfordville

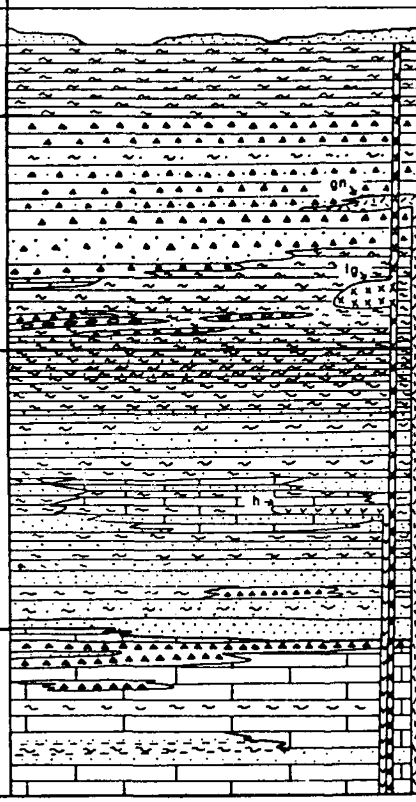
*Personal communication with J. Lyons, Dartmouth College, 1991.

Table 3. Mineralogic characteristics of the rocks of the Orfordville formation (after Lyons 1955).

Rock	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
No. of sections	6	7	3	1	6	1	1	1	4	4	1	1	5	1	4	8	1	1	7	3	8
Quartz	18	20	55	10	50	20	35	50	50	24	48	20	60	33	20	50	10	90	40	75	31
Plagioclase	30	30	20	—	25	35	51	10	10	30	—	30	—	55	45	20	—	—	25	—	30
Calcite	5	t	—	83	x	20	—	—	t	—	—	—	t	—	5	x	85	—	t	—	3
Ankerite	—	—	—	—	—	—	—	—	—	—	—	—	t	—	5	—	—	—	—	—	—
Muscovite	t	—	—	—	5	10	5	10	15	—	—	—	15	2	7	15	2	9	3	8	2
Biotite	t	—	t	—	x	—	2	15	10	10	—	3	10	1	2	5	—	1	10	t	12
Chlorite	6	8	10	5	15	15	5	5	5	—	—	2	10	5	16	10	—	—	t	—	2
Hornblende	35	33	10	—	—	—	—	—	—	30	5	20	—	—	—	—	—	—	t	—	8
Actinolite	—	—	—	—	—	—	—	—	—	—	—	—	—	2	—	—	—	—	—	—	—
Clinozoisite	3	6	2	—	4	t	—	—	2	4	45	25	—	t	—	—	—	—	6	—	9
Garnet	t	—	t	—	t	—	—	2	7	2	2	—	5	—	—	—	—	—	t	—	2
Staurolite	—	—	—	—	—	—	—	5	—	—	—	—	—	—	—	—	—	—	—	—	—
Kyanite	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	15	—
Microcline	—	—	t	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	15	—	—
Apatite	1	1	1	—	x	—	t	1	t	t	—	t	t	t	x	x	—	—	1	—	1
Zircon	—	—	—	—	t	—	—	t	—	t	—	—	t	—	—	t	—	—	—	t	t
Allanite (?)	—	—	—	—	—	—	—	t	t	—	—	—	—	—	—	—	—	—	t	t	t
Tourmaline	—	—	—	—	t	—	—	—	x	—	—	—	t	—	t	t	—	x	t	—	t
Sphene	1	2	—	2	t	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	t
Pyrite	—	x	—	—	—	—	—	—	—	—	—	t	—	—	x	t	1	—	—	2	—
Magnetite	x	x	2	—	1	t	2	2	1	t	—	—	t	2	x	x	—	x	—	—	t
Ilmenite	1	x	—	—	t	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Carbon	—	—	—	—	—	—	—	—	t	—	—	—	—	—	—	t	2	—	—	—	t
% An in plag.	23–30	6–10	9–16	—	5–11	9	7	28	20–50	38–44	—	10	—	6	34–40	5–11	—	—	5–30	—	10–60

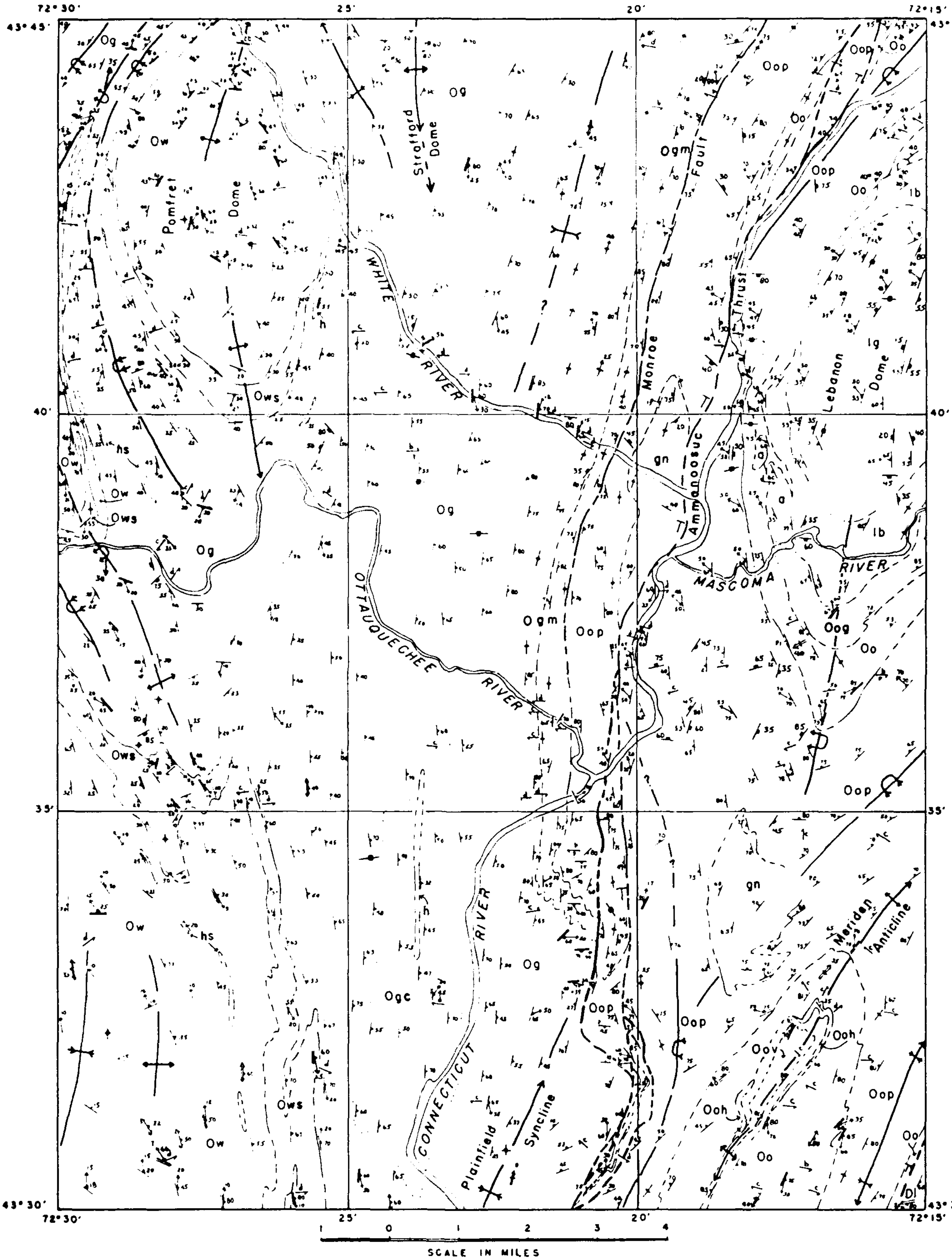
x = present in 50% or more of thin sections; t = present in less than 50% of thin sections, or in very minor amounts in some sections.

1. Hornblende schist; Post Pond volcanics; amphibolite facies.
2. Hornblende schist; Post Pond volcanics; albite-epidote-amphibolite facies.
3. Hornblende-chlorite schist; Post Pond volcanics; albite-epidote-amphibolite facies.
4. Marble; Post Pond volcanics; albite-epidote-amphibolite facies.
5. Chlorite schist; Post Pond volcanics; greenschist facies.
6. Chlorite schist; Post Pond volcanics; greenschist facies.
7. Quartz-feldspar schist; Post Pond volcanics; greenschist facies; relict agglomeratic structure; probably originally a quartz keratophyre (sodaclase dacite).
8. Staurolite schist; amphibolite facies.
9. Mica schist; amphibolite facies.
10. Hornblende schist; amphibolite facies.
11. Epidote granulite; amphibolite facies.
12. Hornblende schist; albite-epidote-amphibolite facies.
13. Mica schist; albite-epidote-amphibolite facies.
14. Feldspathic schist; albite-epidote-amphibolite facies; originally a quartz keratophyre (?).
15. Fedspathic chlorite schist; albite-epidote-amphibolite facies (disequilibrium); metamorphosed volcanic?
16. Mica-quartz schist or phyllite; greenschist facies.
17. Recrystallized limestone; greenschist facies.
18. Hardy Hill quartzite; greenschist facies.
19. Biotite gneiss; amphibolite facies; metasomatized Orfordville.
20. Kyanite schist; amphibolite facies; metasomatized Hardy Hill.
21. Hornblende-biotite gneiss; amphibolite facies; metasomatized Orfordville.



AGE	FORMATION	SYMBOL	LITHOLOGY	THICKNESS IN FEET	PLUTONIC ROCKS
QUATERNARY	DRIFT AND ALLUVIUM		Till, glacial outwash, varved clay, and alluvium	0-200	
LOWER DEVONIAN	LITTLETON FORMATION	Dl	Black mica schist and quartz-mica schist	1500+	Lebanon granite and associated rocks (lg) (Devonian)
MIDDLE SILURIAN	FITCH FM. CLOUGH QTZT.		These four formations absent from this area because of the Northey Hill thrust	4000±	
UPPER ORDOVICIAN(?)	AMMONOOSUC VOLCANICS ALBEE FM.				
MIDDLE ORDOVICIAN(?)	ORFORDVILLE FORMATION	Oop Ooc Oo Oov Ooh Oo	Black to tan phyllite, mica schist, and quartz-mica schist, commonly containing porphyroblasts of biotite or garnet (Oo); upper part of formation composed chiefly of hornblende or chlorite schist (Oop = Post Pond volcanic member); lentils of gray marble (Ooc); discontinuous meta-quartz conglomerate (Ooh = Hardy Hill quartzite member); lentils of hornblende or chlorite schist (Oov = volcanics?)	1500-2000 3500-4000 0-300	Lit-par-lit and other gneiss of uncertain origin and age (gn) Intrusive hornblende schist of uncertain age (h)
	GILE MOUNTAIN FORMATION	Ogm Og Ogc Og Ogv	Tan quartz-mica schist and quartzite with minor interbedded gray to black pelitic schist (Og); black phyllite or schist with thin interbeds of tan quartz-mica schist (Ogm = Meetinghouse slate member; possibly equivalent to Oo) black calcite-quartz schist, with interbedded pelitic schist (Ogc); lentils of hornblende schist (Ogv)	6500± 1500±	
	WAITS RIVER FORMATION	Ows Owv Ow	Rusty-weathering calcite-mica schist, with interbedded mica schist, quartz-mica schist and quartzite (Ow); hornblende schist with minor interbedded pelitic and psammitic schist (Ows = Standing Pond amphibolite member); lentils of hornblende schist (Owv)	4000+ 125-650	

Figure 16. Position of Orfordville formation in relation to other bedrock in Hanover (from Lyons 1955).



1 0 1 2 3 4

SCALE IN MILES

Figure 17. Tectonic map of the Upper Valley (from Lyons 1955).

Structural Symbols

- Strike and dip of beds
- Strike and dip of overturned beds
- Strike and dip of foliation or schistosity
- Strike of vertical foliation or schistosity
- Horizontal schistosity
- Strike and plunge of linear element
- Strike of horizontal lineation
- Strike and dip of axial plane of minor fold
- Strike and dip of axial plane of minor fold, with strike and plunge of fold axis
- Strike and dip of axial plane of minor fold, with horizontal fold axis
- Top of formation as deduced from
  - b - primary bedding features
  - c - cleavage - bedding relations
  - d - drag folds
  - p - pillow structure
- Anticline, showing trace of axial plane and bearing and plunge of axis
- Syncline
- Overturned anticline, showing trace of axial plane, direction of dip of limbs, and bearing and plunge of axis
- Overturned syncline
- Strike and dip of joints
- Fault

formation is now considered equivalent to the Partridge formation (Lyons et al. 1986) and the local granites are of Ordovician age. The Orfordville formation also has a Hardy Hill member (Ooh) of gray to white quartzite and quartz conglomerate that is locally converted to feldspathic gneiss.

Structure in the bedrock is complicated by the superposition of numerous minor folds on the major structures (Fig. 17). Most outcrops show essential parallelism of cleavage and bedding, possibly because of isoclinal folding (Lyons 1955). Axial-plane, bedding, slip and fracture cleavage are present, while the dominant cleavage is the axial-plane type (Lyons 1955). The bedrock bedding, schistosity and faults generally strike north–northeast and dip west–northwest at steep angles (Hodges et al. 1976).

The Ammonoosuc fault (Fig. 17) follows the west bank of the Connecticut River through much of Norwich, Vermont. The fault plane has brecciated and silicified rock and crumpled and contorted cleavage with some ultramylonite (Hadley 1950). Bedrock fractures associated with the fault zone may explain the higher groundwater yields from wells in the zone (Hodges et al. 1976).

Current thinking is that the Ammonoosuc fault is a Mesozoic normal fault dipping 35° to the west with its drop side (west side) displaced nearly 2.5 miles.* Until recently, the Ammonoosuc Fault was considered a thrust that moved less metamorphosed rocks on the west over more highly metamorphosed rocks on the east along a zone that dipped 30–50° west, with a displacement of about 3 miles (Fig. 18). From the perspective of possible effects on local groundwater movement, whether this fault is a thrust or normal fault does not matter.

*Personal communication with J. Lyons, Dartmouth College, 1991.

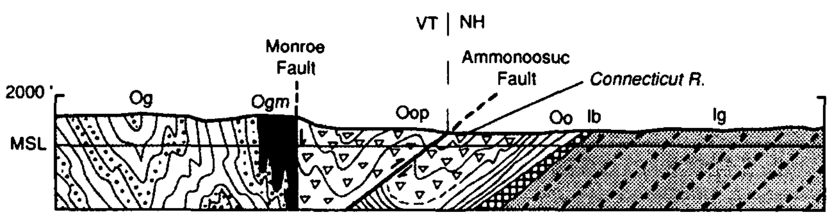


Figure 18. Structural cross section 3 miles south of CRREL (after Lyons 1955); Og—*Gile Mountain formation,* Ogm—*Meetinghouse slate,* Ib—*Lebanon border gneiss,* Ig—*Lebanon granite.*

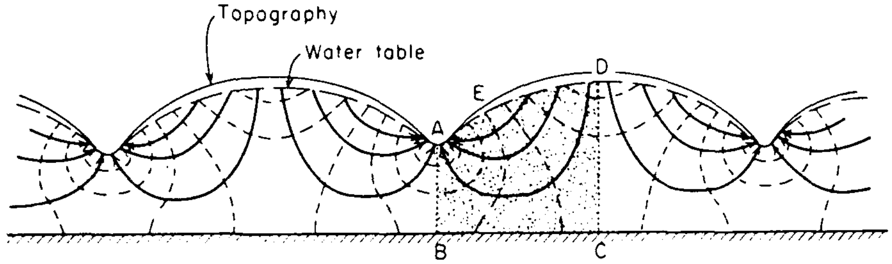


Figure 19. Groundwater flow net in a two-dimensional vertical cross section through a homogeneous, isotropic system bounded on the bottom by an impermeable boundary. The arrows show the direction of groundwater flow; the dashed lines are lines of equal flow potential (from Freeze and Cherry 1979; originally from Hubbert, M.K. [1940] Theory of ground water motion. Journal of Geology, *48: 930; used with permission of the University of Chicago Press, Chicago, Illinois, U.S.A.).*

GEOHYDROLOGY

Fundamentals of groundwater flow

Groundwater flow is an integral part of the hydrologic cycle. Water enters the ground through precipitation and infiltration and exits through stream flow and evapotranspiration. The flow of subsurface water, entering the groundwater system on the hills and discharging into streams and valleys, is shown in Figure 19. This sketch is an idealized vertical cross section of groundwater flow for a humid area such as New England. The water table and flow directions roughly mimic the surface topography. No flow occurs across the hills or streams and these imaginary boundaries are called groundwater divides.

The flow of fluids in the subsurface can be described by Darcy's law

$$Q = KiA \tag{1}$$

where Q = volume of discharge
A = area
K = hydraulic conductivity
i = hydraulic gradient.

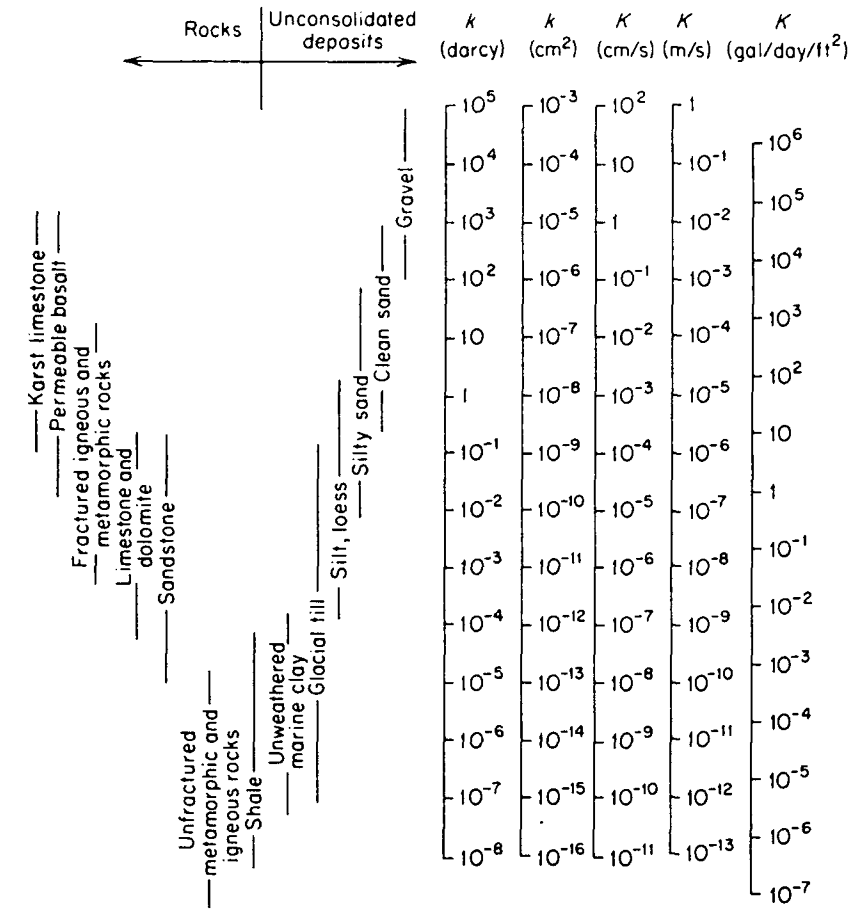
The hydraulic conductivity K is a measure of the ease of fluid movement through a porous medium and is a function of the geometry and connectivity of the voids (pores) in the rock or sediment and the fluid density and viscosity. Hydraulic conductivity is sometimes erroneously expressed as permeability. Permeability, or intrinsic permeability, k, is a function of the medium only, and not of the fluid properties. However, permeability and hydraulic conductivity are related by the following expression

$$K = k\rho g/\mu \tag{2}$$

where k = intrinsic permeability
μ = viscosity of the fluid
ρ = density of the fluid
g = gravity.

The range of hydraulic conductivity values for geologic materials is considerable, spanning 14 orders of magnitude. Typical values of hydraulic conductivity and permeability of different geologic materials are given in Figure 20. Even within one material type, the range of permeability is large and can vary greatly within one sample. Therefore, in the measurement of a hydraulic conductivity of a hydrologic unit, we are more concerned with the exponent of the value rather than the precise value. The hydraulic conductivity can be measured in a single well or piezometer using a slug or bail test or the borehole dilution method. More elaborate pump tests sample a larger volume of the medium but require more than one well. Hydraulic conductivity can also be measured in the laboratory.

The hydraulic gradient is the rate of change of the hydraulic head h with distance l ($i = dh/dl$). The hydraulic head is the flow potential, which is the sum of the pressure head and the elevation head, and is generally obtained by measuring the water elevation in a well or piezometer. The water level in a well reflects the hydraulic head or piezometric surface of the sediments at the depth where the well is completed. Therefore, water levels from nearby wells may not be comparable if they are not completed in the same hydrologic unit. Figure 21 is a sketch showing how the piezometric surface can be different for different aquifers and how



Conversion Factors for Permeability and Hydraulic Conductivity Units

	Permeability, k*			Hydraulic conductivity, K		
	cm²	ft²	darcy	m/s	ft/s	gal/day/ft²
cm²	1	1.08×10^{-3}	1.01×10^{8}	9.80×10^{2}	3.22×10^{3}	1.85×10^{9}
ft²	9.29×10^{2}	1	9.42×10^{10}	9.11×10^{5}	2.99×10^{6}	1.71×10^{12}
darcy	9.87×10^{-9}	1.06×10^{-11}	1	9.66×10^{-6}	3.17×10^{-5}	1.82×10^{1}
m/s	1.02×10^{-3}	1.10×10^{-6}	1.04×10^{5}	1	3.28	2.12×10^{6}
ft/s	3.11×10^{-4}	3.35×10^{-7}	3.15×10^{4}	3.05×10^{-1}	1	5.74×10^{5}
gal/day/ft²	5.42×10^{-10}	5.83×10^{-13}	5.49×10^{-2}	4.72×10^{-7}	1.74×10^{-6}	1

*To obtain k in ft², multiply k in cm² by 1.08×10^{-3}.

Figure 20. Range of values of hydraulic conductivity and permeability for different rock and sediment types (from Freeze and Cherry 1979; reprinted with permission of Prentice Hall, Englewood Cliffs, New Jersey).

water levels in wells differ in each condition. All types of aquifers can be present within one area.

Hydraulic conductivity K and hydraulic gradient i are used to characterize the subsurface flow regime. Sediments with high K values will move large quantities of water quickly and are called aquifers. Sediments with low hydraulic conductivities impede the movement of subsurface fluids and are called aquicludes or aquitards. For the same K value, an increase in i will increase the flow, as indicated in eq 1.

The effects of i and K on the groundwater flow regime were demonstrated in a study by Freeze and Witherspoon (1967). They constructed a numerical model to simulate a simple regional groundwater flow regime in a homogeneous

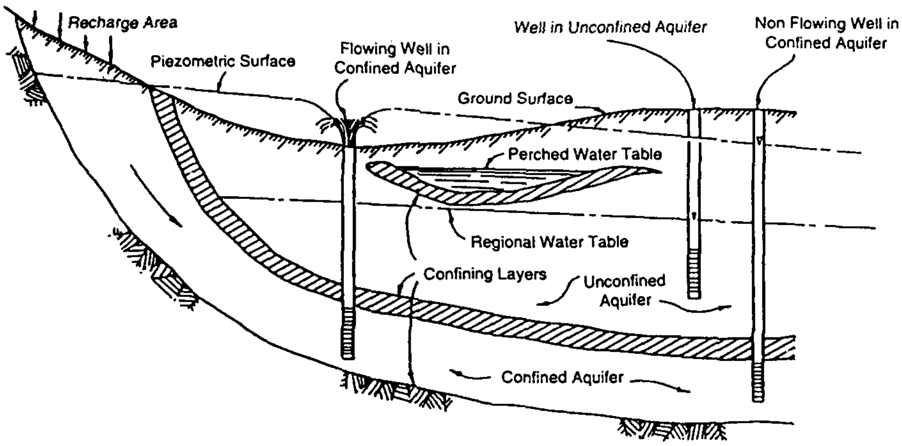
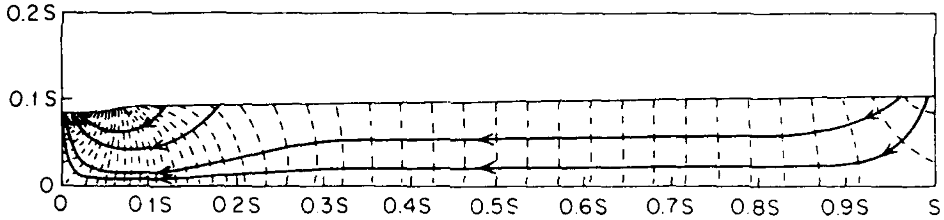
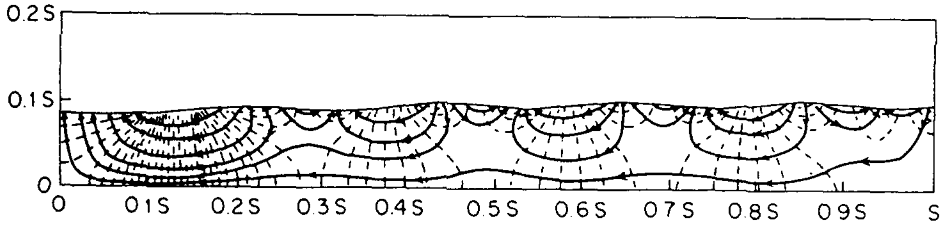


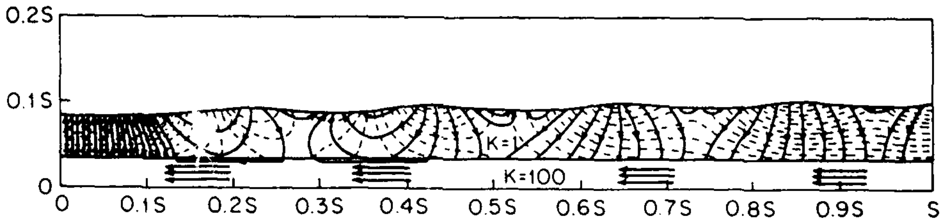
Figure 21. Water levels in wells completed in different types of aquifers.



a. In a region with gentle topography.



b. In a region with hilly topography. Now the groundwater flow has several local systems, induced by the hilly terrain, above the regional flow pattern.



c. In a region with hilly topography with a more permeable layer below. The more permeable layer acts as a conduit for the groundwater flow.

Figure 22. Numerical simulation of a homogeneous regional groundwater flow system. The arrows show the direction of groundwater flow; the dashed lines are lines of equipotential (from Freeze and Cherry 1979; originally from Freeze and Witherspoon [1967] Theoretical analysis of regional groundwater flow: 2. Effect of water-table configuration and subsurface permeability variation. Water Resources Research, *3: 625 and 628).*

material with a gently dipping topography. The resulting flow system is shown in Figure 22a. To demonstrate the effect of topography, a hilly upland topography was added to the previous model. This created several topographically induced local flow systems above the larger scale regional flow path (Fig. 22b). Next, the porous media were altered to a layered system with the hydraulic conductivity of the lower sediment 100 times greater than the upper sediment. The more permeable layer serves as a conduit for flow and changes the flow system to that shown in Figure 22c. These models demonstrate the complicated nature of the groundwater flow for even very simple geology and topography, and help us to visualize the effect of these parameters on that flow.

Upper Valley groundwater setting

The CRREL site is located within the middle of the Connecticut River drainage basin, commonly referred to as the Upper Connecticut River Valley, or simply the Upper Valley. The Connecticut River drains an area of 4092 miles^2. Discharge ranges from a minimum of 82 ft^3/s to a maximum of 136,000 ft^3/s, with an average discharge of 7121 ft^3/s as recorded at the West Lebanon gage location, 5.6 miles downstream of CRREL (Blakey et al. 1989). Average discharge of the Connecticut River at a site approximately 0.5 miles upstream from CRREL (near the Norwich town well) is estimated to be 4900 ft^3/s (Hodges et al. 1976).

The river is pooled behind Wilder Dam, which is 4.4 miles downstream of CRREL. The Wilder Dam reservoir extends 30 miles upstream to the Piermont–Haverhill, New Hampshire, area and has a normal water residence time of 2–5 days, depending on discharge at the dam (3.5 days with average discharge). The river near CRREL is approximately 500 ft wide, fluctuates from 380 to 385 ft above msl and averages about 33 ft in depth.*

The climate in the Upper Valley is humid, with four distinct seasons. The 30-year mean monthly temperatures range from 18°F (January) to 69°F (July). Mean monthly air temperatures measured at the CRREL weather station between 1972 and 1982, along with the 30-year mean based on data from the Hanover station, are displayed in Figure 23 (Bates 1984). Precipitation averages 33.3 in./year, based on a 10-year average (1972 to 1982), with the highest rainfall, 3.7 in./month, occurring in June. Figure 24 displays the 10-year monthly average precipitation measured at the CRREL site

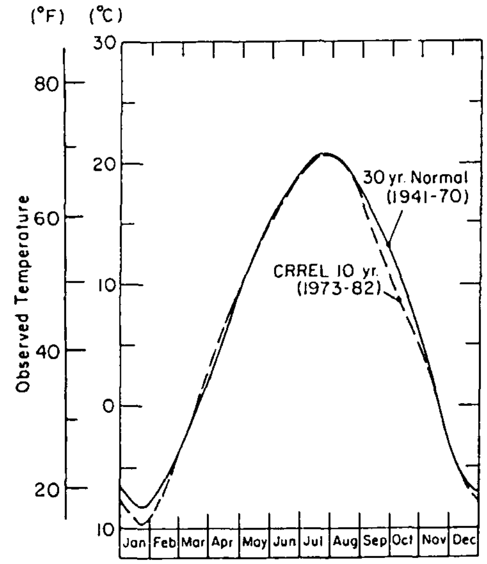


Figure 23. Temperature data from CRREL (dashed line) and Hanover, New Hampshire (after Bates 1984).

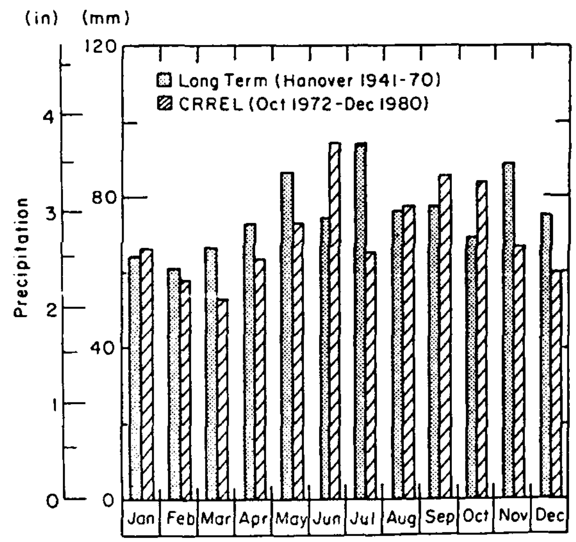


Figure 24. Precipitation data from CRREL and Hanover, New Hampshire (after Bates 1984).

and the 30-year averages from the Hanover station.

Hodges et al. (1976) quote an annual precipitation in Hanover of 35.8 in./year with yearly snowfall of 74.4 in. Of the 35.8 in. of precipitation, 15 in. of that returns to the atmosphere as evapotranspiration, and 20.8 in. becomes runoff, either overland or infiltrating into the ground and entering streams as groundwater. Groundwater discharge into streams is significant and sustains the stream flow during dry periods and winter months. During spring runoff when stream levels are high, the water moves into the adjacent aquifers. Similarly,

*Personal communication with M. Ferrick, CRREL, 1991.

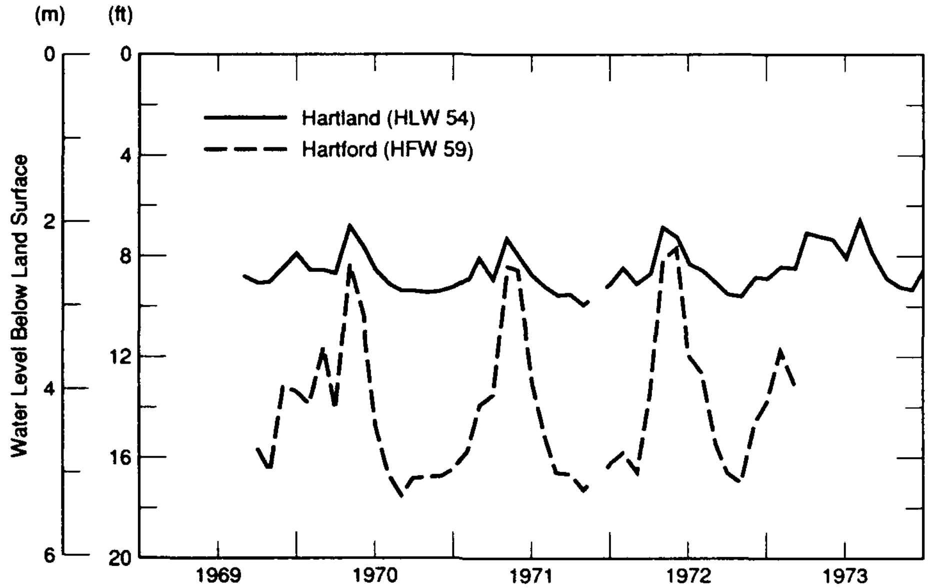


Figure 25. Seasonal fluctuation of water levels in two wells in the White River Junction area (after Hodges et al. 1976).

pumping of these watercourse aquifers induces recharge from the adjacent rivers. Monthly water level measurements in two unconfined aquifers in White River Junction, Vermont, reflecting the seasonal recharge into groundwater are shown in Figure 25. Precipitation and local stream recharge are generally adequate for the groundwater uses typical of the Upper Valley: primarily houses and farms.

Groundwater supplies in the Upper Valley occur in fractured bedrock or in small deposits of stratified drift or highly permeable water course aquifers. The bedrock and small stratified aquifers are generally low yield and are good for domestic or stock use. Bedrock aquifers produce from fractures whose distribution and interconnectedness is highly irregular and commonly minimal, thus they typically do not produce high enough water yields for municipal or industrial use. Large-yield well fields are commonly in highly permeable sand and gravel that have large storage capacities or significant recharge from hydraulic connections with large streams and rivers, or both.

Thick glacial tills in the area are generally low-permeability sediments and, therefore, are limited groundwater producers. The deposits of stratified gravels, sands, silts and clays that are common in the valleys have highly variable porosity and permeability and thus their potential for groundwater is limited, although they are often adequate for domestic use (Cotton 1976).

The high-yield aquifers in the Upper Valley are watercourse aquifers of highly permeable sands and gravels lying along stream channels and in close hydraulic continuity with the stream. These deposits are primarily coarse sediments from streams that were within or adjacent to ice masses near the end of the Pleistocene glaciations. The sand and gravel deposits are overlain by fined-grained lake sediments, primarily varved silts,

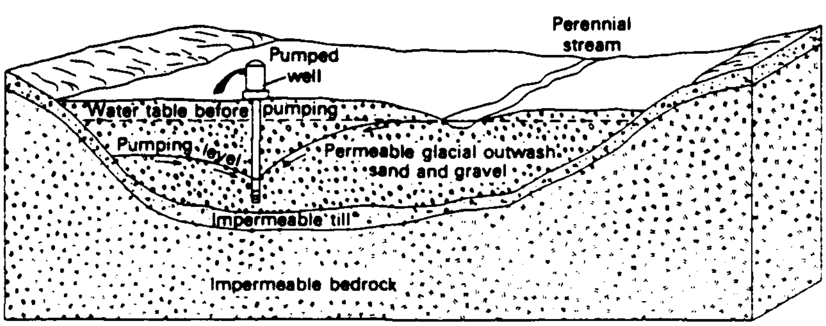


Figure 26. Typical New England water course aquifer (from Sinnot 1982).

deposited in Pleistocene Lake Hitchcock and Lake Upham. Groundwater pumping from these aquifers produces recharge from the stream, and when the permeability between the well field and the stream is high, the aquifer yields are exceptionally large. These very productive aquifers are largely confined to stream valleys and thus are of relatively limited extent, which constrains extensive development. Figure 26 illustrates a typical example of a water course aquifer showing the influence of pumping on recharge from the nearby stream (Sinnott 1982). Additional details on the groundwater resources in the region can be found in Cederstrom and Hodges (1967), Cotton (1976) and Hodges et al. (1976).

CRREL geohydrology

The geology of the CRREL site can be divided into three hydrologic units: an esker, lake sediments and fractured bedrock. (For simplicity, the geological origin of the coarse-grained, high-yield sediments, whether esker, kame or other, will not be debated and will be assumed to be an esker for the remainder of the discussion.) The groundwater flow at CRREL is dominated by an esker having high permeability and high well yields. It is surrounded by lake deposits of less permeable varved silts and clays. All of this overlies a complexly folded and irregularly fractured bedrock of schist–phyllite. A sketch of the configuration of these three units based on the geology of the area is shown in Figure 27.

The esker is used as a source of industrial water for the refrigeration system at CRREL and for drinking water supply for the towns of Hanover and Norwich. The Norwich town water well intersects the esker approximately 1 mile north of CRREL on the Vermont side of the river (see Fig. 8). The Hanover town well is approximately 1000 ft north of CRREL and is used only on demand during the summer. Within 1 mile of CRREL, the lake sediments and bedrock are used only for small domestic water supplies, mainly in Vermont. The Hanover side of the river is on town water (which is primarily surface water) except for a few residences north of CRREL.

Esker

The esker extends for 50 miles along the Connecticut River from Bradford to White River Junction, Vermont. South from Bradford, Vermont, it crosses the river to New Hampshire just north of CRREL and continues south along the New Hampshire side of the river for several miles (see Fig. 8). Although it partially follows a ridge along the river, the presence of the ridge is only coincidental since the esker is older than and is overlain by lake sediments.

Good exposures of the esker exist in several gravel pits in the area, including two exposures immediately behind CRREL (between CRREL and the river at the south end of CRREL) and just north of CRREL. These exposures display the coarse-grained sand and gravel of the esker. The exposure

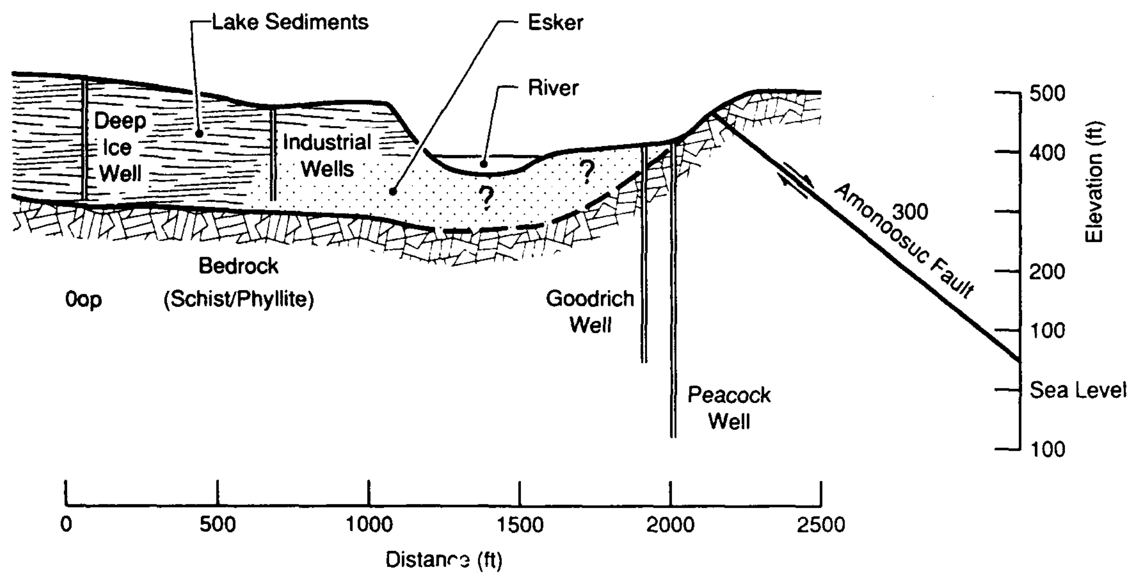


Figure 27. Geohydrologic units at CRREL.

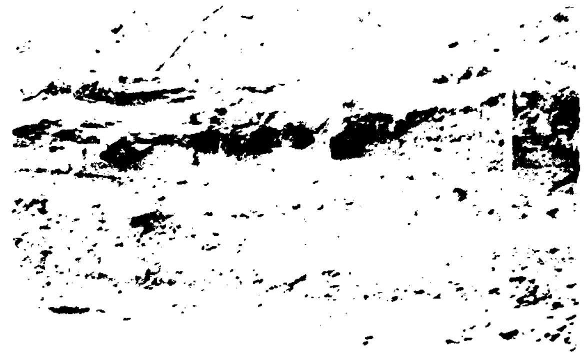


Figure 28 Views of the esker just north of CRREL showing a massive, uniform gray sand layer as well as laminated sand with sizable cobbles and complex cross-bedding sedimentation patterns. The stick shown for scale is 1 m (3 ft).

north of CRREL shows the esker sediments to consist of a thick, homogeneous and only slightly bedded sand layer as well as laminated and cross bedded deposits with gravels. Examples of the sedimentary structures within the esker are shown in the photographs in Figure 28.

At the CRREL site, the esker is overlain by approximately 90 ft of silty and clayey lake sediments (Fig. 10 and 27). Some of the wells at CRREL have penetrated the full thickness of the esker into bedrock. The esker exposed at the Norwich town well is not covered by lake sediments but is overlain by lake sediments on its western flank and just north of the town well, as exposed in a gravel pit. The Norwich town well penetrates the full section of esker into relatively nonpermeable glacial till.

The lateral (east–west) extent of the esker is not entirely known, but has been estimated at 500 ft. Experiences in drilling CRREL well 32-3 indicate that the contact between the esker and the lake sediments is fairly abrupt and steep because the first attempt at this well (approximately 20 ft to the east of its present location and 150 ft deep) totally missed the highly permeable sands and gravels of the esker and had an extremely low yield (1 pt/hr). It is not clear whether the esker continues under the river or not. The USGS ran a marine seismic line along the river, including the area adjacent to the CRREL site, but the data analysis is not yet complete and additional surveys may be needed to define the esker boundaries.

All of the industrial wells at the CRREL site penetrate the esker (wells 32-1 through 32-5, Fig. 10 and Table 1). In addition, several boreholes were drilled into the esker as part of the foundation study for the Frost Effects Research Facility (FERF) building, which lies on top of the esker (wells 31-B1 to 31-C4, Fig. 2). As mentioned earlier, north of the CRREL property, the town of Hanover has an intermittent water supply well in the esker (well 3-1), and there are two shallow wells approximately 0.5 miles north of CRREL (wells 2-1 and 10-146), which may or may not penetrate the esker. Further north where the esker crosses the river into Vermont, the town of Norwich has water supply wells and associated monitoring wells in the esker sediments (see Fig. 11c). Just south of the CRREL property is an abandoned well originally operated by the town of Hanover (well 32–Hanover). No additional wells penetrate the esker in the vicinity.

Much of the information on the CRREL wells, which included the well completion information, has been lost. Screened interval information is available for CRREL wells 32-1 and 32-3. In both of these, a 40-ft section was screened near the bottom

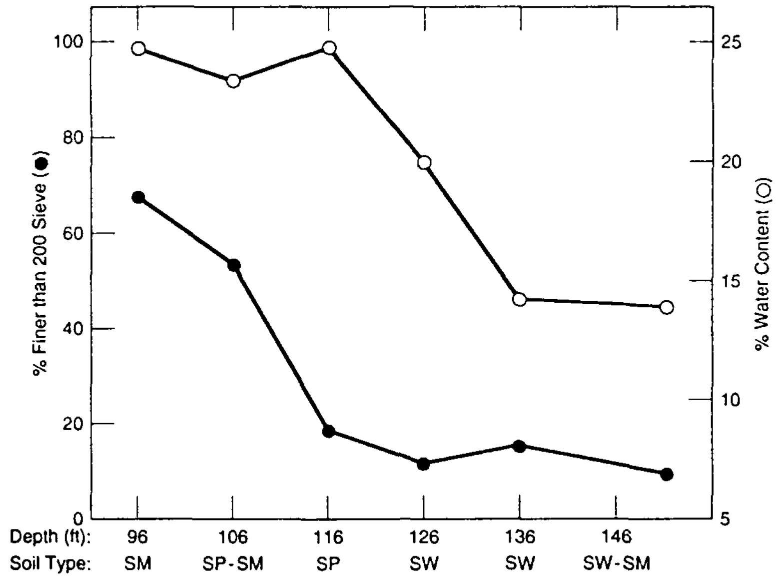


Figure 29. Variation of water content and percent fines with depth, well 31-B5.

of the well. Since the other wells are in the same vicinity and same aquifer, it is believed that they are also screened for 40 ft near the bottom, as appears to be standard practice for these types of wells. The screen slot sizes, however, differ among the wells.*

Sediment logs exist for CRREL wells 32-1, 32-2 and 32-3, the abandoned town well south of CRREL and several boreholes for a foundation study for the FERF, which lies on top of the esker. Simplifications of these logs that penetrate the esker at CRREL are shown in Figure 10 and Appendices B and E. More detailed logs of these wells are available in CRREL Internal Report 1088 (Gatto and Shoop 1991). In general, the logs indicate that the depth of the esker is 70 to 90 ft. The land contours where these wells are located have changed over the years with the construction of the FERF building and the leveling of the surrounding land.

The foundation study log (31-B5) contains the best geotechnical information on the sediments in the vicinity of the esker. This log is included in full in Appendix E. On this log the esker sediments are classified based on the Unified Soil Classification System as silty sands and poorly graded gravelly sands (SM and SP-SM) at 88 to 115 ft and as poorly graded to well graded sands and gravelly sands (SP, SW and SW-SM) at 115 to 170 ft (bedrock). All the sediments are considered nonplastic. The water content of the esker sediments is in the mid-20% range within the upper part of the esker (above 115 ft) and then gradually drops to 14% between 131 and 170 ft. These water contents reflect the specific retention capacity of the sediment types. The fine-grained soil, expressed as the percent finer than the 200 sieve size, gradually decreases with depth within the esker. The grain size and water content are graphed in Figure 29. The lower water contents, along with visual and grain size observations, indicate the coarsening (less silt) of the esker deposits with depth.

A grain-size analysis on sediments from the original CRREL well (32-1) for sediment samples taken between 82 and 150 ft deep (the esker) is shown in Figure 30. The majority of the sediments fall within the size range of a medium to fine sand.

Although no aquifer tests are available to compute the hydraulic conductivity of the esker at CRREL, the grain size distribution can be used to calculate an estimate. Several empirical formulas exist for estimating the hydraulic conductivity from grain size distribution. For clean, cohesionless sands and gravels, the Hazen equation provides a good rough approximation

$$K = Cd_{10}^{2} \tag{3}$$

where C = a constant depending on units: 1.0 for K in centimeters/second and d in millimeters; 1.83×10^6 for K in feet/day and d in inches.

d = the grain-size diameter at which 10% by weight of the soil particles are finer.

*Personal communication with D. Gaskin, CRREL, 1991.

The shaded area of the grain-size distribution curve in Figure 30 shows that at d_{10}= 0.03 mm (1.2 × 10^{-3} in.) K is approximately 10^{-3} cm/s (3 ft/day). This lies within the clean sand or silty sand range shown in Figure 20 and also agrees with the information on the soil type from the geotechnical log from well 31-B5.

The nature of the hydraulic properties of the esker are also indicated by the pump records of the CRREL wells, which suggest a highly permeable aquifer with large yields. The pumps operate on demand and at irregular intervals, but the flow volume and operating time are recorded. From these, the well discharge can be calculated. Based on a monthly average for November 1990 to March 1991, the well discharge rates are shown in Table 4. Even with the wide range among the wells, the aquifer would be considered high yield.

The groundwater elevations in the CRREL well field have been measured only sporadically; the information that does exist is listed in Table 4. Some of these measurements were taken while the pump to an adjacent well was running, as noted on the table. The most current water level measurements are from wells 32-4 and 32-5. (Well 32-5 has been completed but is not yet operational.) Water level in well 32-4 was 107 ft below surface with the pump running and 91 ft static. Well 32-5 was measured at the same time and was 100 ft below surface (with the pump to well 32-4 running). Historical measurements of static water levels depths are 80 ft for well 32-1 (January 1963) and 81.3 ft in well 32-3 (September 1986), both relative to the top of the casing. The personnel using these wells tell us that the water levels are similar between wells. Notes on water level measurements during the completion of well 32-1 indicate that the well was hydraulically connected to the river.

Water level information recorded during drilling of well 31-B5 adds both insight and confusion to the groundwater situation in the esker. The log of the well indicates a fairly constant perched water table at 3 ft (which was monitored after PVC was placed in the well). The water table was encountered between 90 and 92 ft, just below the top of the esker. Above 90 ft the sediments are described as dry or moist. After the depth to bedrock was obtained, a PVC pipe was placed to a depth of 137.5 ft to isolate the perched water from the groundwater, and the water levels both inside and outside the PVC were monitored for several days. The water level outside the PVC remained at 3 ft, indicating the perched water table conditions, while the water level inside the PVC was at a 14-ft depth, indicating that the esker is a confined aquifer. This 14-ft water level, however, disagrees with all other water levels taken at the CRREL wells.

Water level measurements at the CRREL site

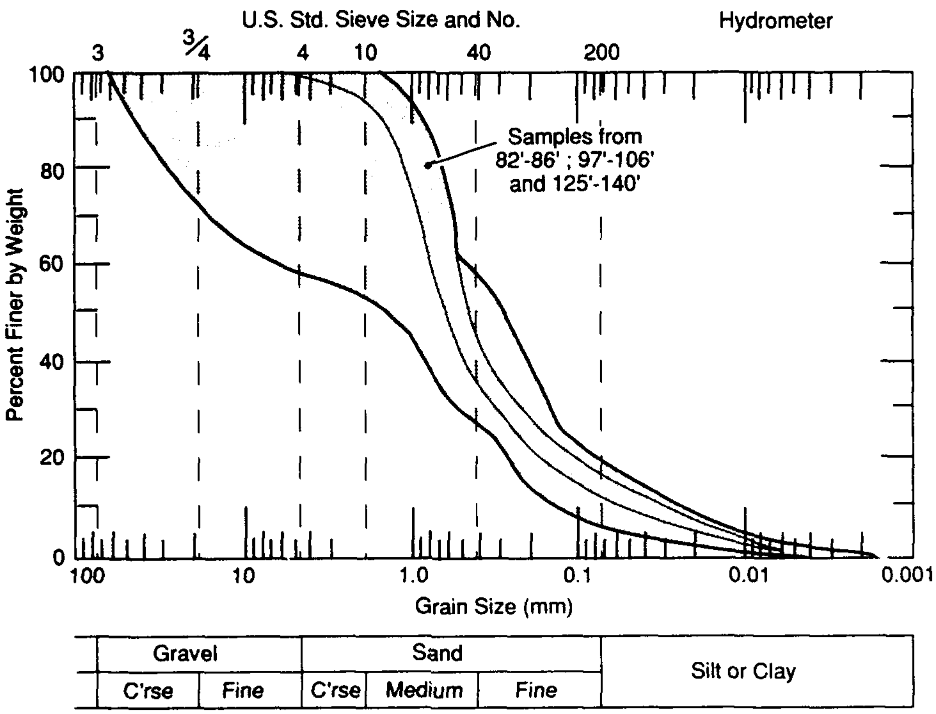


Figure 30. Grain size distribution for sediments from CRREL well 32-1.

Table 4. Groundwater well information from the CRREL site.

Well no.	Total depth (ft)	Date drilled	Screened interval	Present ground elevation (ft above msl)*	Original surface elevation (ft above msl)*	Depth to water table (ft)	Reference	Date measured	Well discharge rate (gal./min.)††
32-1	150	12 Sept 57	101–146	467.2	462.4	80	top of casing**	Jan 1963	457 to 822
32-2	147	9 Nov 63	unknown	468.5	462.1	—	00	—	approx. 300
32-3	167	18 Aug 76	110–150	462.6	unknown	81.3†	top of casing	Sept 1986	646 to 661
32-4	150	1986	unknown	465.9	unknown	91	unknown	1986?	121 to 141
32-5	unknown	1988	unknown	468.5	unknown	100†	unknown	1988	not used

* Surveyed using GPS by Jeff Meyers (March 1991).
† Measured with pump of well 32-1 running.
** Top of casing elevations are unknown for all wells.
†† Measured for December 1990 to April 1991.

are not complete enough to determine water level contours or hydraulic gradients. The Norwich town wells indicate small hydraulic gradients and connectivity to the river. Although monitor wells installed during the phase I site assessment (winter 1991–92) indicate a flat water table with a cone of depression at the pumping wells (App. F), current groundwater levels should be obtained and monitored for all the CRREL wells.

The most accurate information on the hydraulic properties of the esker is from a study of the Norwich town well (hydraulic conductivity was not measured during the phase I study). Since the Norwich well field is also located in the esker and behaves in much the same way as the CRREL wells (high permeability, high yield), the information from this well likely represents the conditions at the CRREL site.

The town of Norwich water supply wells and associated monitoring wells were originally studied by the USGS as part of an assessment of the groundwater availability in the White River Junction area (Hodges et al. 1976). Later, additional wells were drilled and extensive aquifer tests were conducted and documented in Caswell (1990) and Winkley and Caswell (1990). As requested by the State of Vermont, the Norwich town well was tested to see if the well water should be treated as "true" groundwater or as surface water from the Connecticut river. Constant rate and variable rate pump tests were performed using two pumping wells and nine observation wells to determine the recharge and boundaries of the aquifer as well as aquifer capacity and transmissivity.

The Norwich town well is located on the axis of the esker, about 300 ft from the Connecticut River. At this location, the esker is about 170 ft thick, overlying glacial till. No lake sediments cover the esker at the Norwich town wells, but they do cover the esker nearby. The water table levels are around 65 ft below the surface; therefore, at this site the aquifer is definitely unconfined.

Based on the Norwich pump tests, the hydraulic conductivity of the esker is 0.1 cm/s (283 ft/day). The new (12-in. diameter) well has a specific capacity (discharge per foot of drawdown in the well) of more than 300 gal./min per ft. Even at a very high pumping rate (975 gal./min) the drawdown cone around the pumping wells was relatively small and the hydraulic gradients are very low (nearly flat), on the order of 0.001. The transmissivity of the aquifer (the hydraulic conductivity multiplied by the saturated thickness of the aquifer) is 275,000 gal./day per ft, indicating a very good well for groundwater exploitation. For the aquifer thickness of 100 ft, the hydraulic conductivity is 27,500,000 gal./day, or 0.15 cm/s. This is two orders of magnitude higher than the hydraulic conductivity calculated from the grain size distribution from the CRREL well. Field measurements of hydraulic conductivity may be higher than empirical estimates, which are based on the amount of fines because, in the field, the soil is layered and the field hydraulic conductivity is controlled by the coarser layers. The field measurements can also be several orders of magnitude higher than that determined in laboratory tests and are considered far superior to the laboratory measurements.

Water level and temperature measurements in the Norwich town wells and the river indicate a clear connection between the river and the aquifer (as was also indicated by historical data from CRREL well 32-1) and that pumping induces recharge from the river.

Although the data from the Norwich town well can be used as an approximation of the conditions at CRREL, site-specific data from CRREL should be obtained as part of future CRREL site assessments.

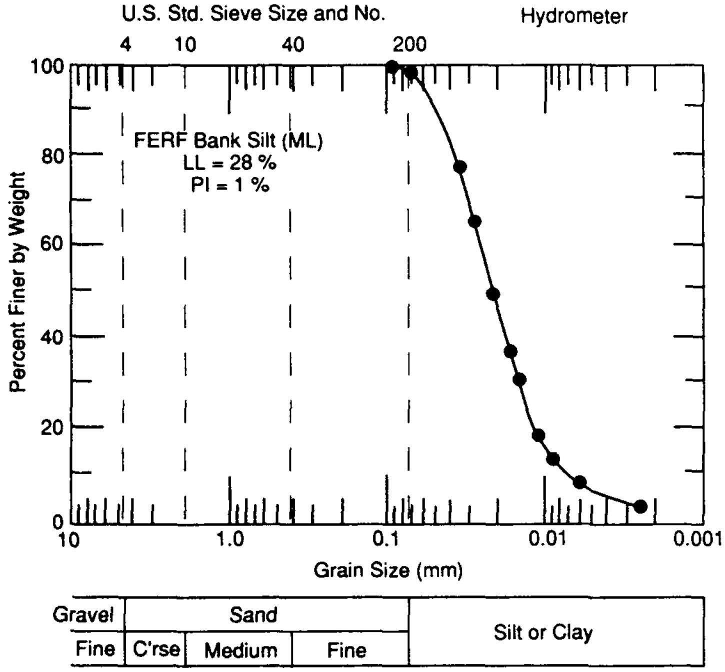


Figure 31. Grain size distribution curve and Atterberg limits of the varved silts and clays taken from the bank south of the FERF building.

Lake sediments

The lake sediments consist primarily of varved silts and clays with some fine sand layers. Since the lake formed after the glaciers retreated, the remainder of the sediments on CRREL property are lake sediments, including the entire area under the main lab and down to the esker, and overlying the esker.

Several good logs penetrate the lake deposits at and near CRREL. The logs from the foundation study for the FERF building document the lake sediments above the esker deposit (wells 31-B1 to B7 and 31-C1 to C4). Logs are also available from an underground storage tank site assessment just south of CRREL on Route 10 (wells 7-B1, 7-B2 and 7-B3). Recently (16 and 17 April 1991), additional foundation borings were completed for a building to be located just north of the Facilities Engineering building (logs of these wells are available in Gatto and Shoop [1991]). None of these borings intercepted the water table. These logs characterize the lake sediments as varved silts and clays and fine sands. Exposures of these sediments are also abundant in the area, including a bank cut just north of CRREL, which clearly shows the contact and the contrasting nature of the esker deposit and the varved and laminated lake sediments above.

The geotechnical logs from the FERF foundation study show the penetration resistance of the sediments, the water content, the plasticity and the percent of fines passing the 200 sieve (opening of 0.075 mm), and the soil classification based on the Unified Soil Classification System. These logs indicate that the lake sediments are primarily fine-grained soils with 50 to 100% by weight passing the 200 sieve, although coarse layers are not uncommon. The high water contents of the fine-grained layers are indicative of the amount of water that these sediments can hold in retention. These finer grained sediments are also likely to retain contaminants, as discussed later.

A grain size distribution curve of the lake sediment from the bank on the south side of the FERF building is shown in Figure 31. This soil is classified as ML, a low-plasticity clayey silt. The grain size distribution (d_{10} = 0.004 mm) and the Hazen formula give the hydraulic conductivity of the lake sediments as roughly 10^{-5} cm/s (10^{-2} ft/day). This compares favorably with the hydraulic conductivity range of this soil type shown in Figure 20. Laboratory measurements show the hydraulic conductivity of the lake sediments above the esker to be 6×10^{-4} cm/s (1.7 ft/day)* (App. G).

In Caswell's (1990) study, the hydraulic conductivity of the lake sediments is estimated at 0.1 ft/day (0.02 cm/s). Although he does not state how he determined this value, we assume it is based on field permeability tests. As mentioned before, field determined hydraulic conductivity values are often several orders of magnitude higher than laboratory values, since the hydraulic con-

* Personal communication with J. Stark and J. Ingersoll, CRREL, 1991.

ductivity in the field will be controlled by the coarse sediment layers. It is possible that our grain size curve represents a sampling of the finer sediments, or the total sediments, whereas the in-situ sediments are laminated. In laminated sediments, the coarse, high-permeability layers will control the overall permeability of the sediments. Simple field permeability tests should be done at CRREL as part of future site investigation studies.

Bedrock aquifers

The rock types in the area are schist and phyllite, with permeability primarily from stress induced fractures, bedding plane fractures and schistosity. The fractures are fairly irregular, owing to the complicated folding and faulting of the rock. The bedrock depth is approximately 150 ft below the surface at the FERF building and unknown elsewhere at CRREL. The most significant bedrock structure near the CRREL site is the Ammonoosuc fault, originally thought to be a thrust fault, but now believed to be a normal fault with 4-km displacement. The bedrock and the fault outcrop on the west side of the Connecticut River opposite the CRREL site. The wells across the river (wells 9-50 and 9-195) show the depth of bedrock near the river to be 34 to 74 ft. The Britton well (well 29-1) further up the hill shows bedrock at 174 ft.

The hydraulic conductivity of the bedrock aquifers in the area is attributable primarily to interconnected schistosity and fractures. Because of the erratic nature of the fracture occurrence and orientation in these metamorphosed, folded and faulted rocks, the hydraulic conductivity is extremely variable.

Water levels in the bedrock wells immediately across the river from CRREL are unknown. Further west, up the hill from these wells, the water level is recorded at 50 ft below the surface (well 29-1). This well may or may not have any connection to the lower wells, however.

Water quality

The groundwater at CRREL is used exclusively as an industrial supply to the refrigeration systems supporting the coldrooms and to cool the main laboratory building. The wastewater from these systems is discharged into the Connecticut river and so, even though the groundwater is not used for drinking, it must be free from contamination when discharged.

It would be incomplete to discuss the groundwater of the area without mention of the groundwater quality. The groundwater chemistry is extremely important for two very different reasons. The first and most obvious is that the groundwater must meet the quality requirements for its intended use. The second is the scientific importance of groundwater chemistry in groundwater investigations. The groundwater chemically interacts with the rocks it moves through and this water–rock interaction is a vital clue to the flow path of the fluid. Differences in groundwater chemistry may reflect different flow paths, differences in the mineral composition of the aquifers, geologic structure, or chemical reactions and degradation.

The quality of the groundwater in New England is generally good to excellent. Unfortunately, routine water quality analyses of groundwater samples at CRREL are not available. Data from the phase I site assessment and the Norwich town well are included Appendix H.

Because of the CRREL soil-water chemistry, the CRREL wells are reworked with a chemical treatment (muriatic acid, tatra potassium pyro phosphate) approximately every 4 or 5 years, except for well 32-1, which was pumped for over 26 years before needing treatment. In addition, the reservoir tank where the well water is stored is shut down and scoured to remove the iron deposits every year and the pumps and other equipment are flushed with acid every 6 months.

Generally, the major concerns for water quality in the area are pollution from landfills and from deicing chemicals used on the roads in winter. Small amounts of hydrocarbons were suspected in the soils of a nearby property that once contained underground fuel storage tanks. Details of the assessment of this site are filed with the State of New Hampshire.

Subsurface behavior of TCE

The movement of a contaminant in porous media is a function of the properties of the fluid (chemistry, density, solubility, reactivity, volatility and viscosity) as well as the properties of the media (porosity and permeability and capillary pressures, which include grain and pore shape and size, and chemistry). Some of the basic physical properties of TCE are listed in Table 5. Since TCE is denser than water, its movement in the subsurface is primarily controlled by gravity, although it is also driven by hydraulic gradient and capillary forces and is affected by chemical interactions between water and minerals, and degradation. Since it is largely immiscible and more dense than water, it is considered a Dense Non-Aqueous Phase Liquid, or DNAPL, and will move through

Table 5. Physical and chemical properties of trichloroethylene (TCE) (after Schwille 1988).

Molecular weight :	131.5 g
Solubility in water :	1100 mg/L
Vapor pressure :	58 torr
Sediment/water partition coefficient :	126 mL/g
Density :	1.46 g/cm^3
Boiling point at 760 torr pressure :	87°C
Absolute viscosity :	0.57 centipoise
Kinematic viscosity :	0.39 centistoke
Henry's Law constant for partitioning between air and water :	0.0071 atm m^3/mol
Vapor density relative to dry air :	1.27

the subsurface as a separate phase. However, it is also volatile and slightly soluble and some of the TCE will additionally be present in a soluble phase and a gas phase.

Theory

The movement of immiscible phase liquids through saturated or unsaturated soil is governed by equations for multiphase flow. The continuity equation, or conservation of mass, must be satisfied for each of the phases present

$$\nabla \bullet \rho v = -\delta(\phi\rho)/\delta t \tag{4}$$

where ∇ = differential operator
ρ = density
v = fluid velocity
ϕ = porosity
t = time
δ = partial derivative

and where the velocity of the fluid can be described by Darcy's law. Rewriting eq 1 in terms of Darcy velocity gives

$$v = -(k/\mu)\rho\nabla\Phi_{\mathrm{NAPL}} \tag{5}$$

where v = Darcy velocity ($v = Q/A$)
k = intrinsic permeability
μ = viscosity of the fluid
ρ = density of the fluid
$\nabla\Phi_{\mathrm{NAPL}}$ = flow gradient of the Non-Aqueous Phase Liquid (similar to the hydraulic gradient i in eq 1).

The fluid flow potential is a function of fluid pressure, gravity and capillary (or matric) potential as well as temperature, chemical and electrical potentials.

$$\Phi_{\mathrm{NAPL}} = \Phi_{\mathrm{press}} + \Phi_{\mathrm{grav}} + \Phi_{\mathrm{cap}} + \Phi_{\mathrm{temp}} + \Phi_{\mathrm{chem}} + \Phi_{\mathrm{elec}}\,.$$

For the moment, let's consider only the potential from fluid pressure and gravity, otherwise known as the hydraulic head. For two fluids present, the hydraulic potential of a NAPL is driven by both gravity and by the water flow potential according to the following equation (after Hubbert 1953)

$$\Phi_{\mathrm{NAPL}} = (\rho_w/\rho_{\mathrm{NAPL}})\Phi_w - [(\rho_w - \rho_{\mathrm{NAPL}})/\rho_{\mathrm{NAPL}}]gz \tag{6}$$

where Φ_{NAPL} = flow potential for the NAPL
Φ_w = flow potential for the water
z = elevation from a datum
ρ = density of the fluid (NAPL or water)
g = gravity.

Rewriting in terms of forces gives

$$\mathbf{F}_{\mathrm{NAPL}} = -(\rho_w/\rho_{\mathrm{NAPL}})\,\nabla\Phi_w + [(\rho_w - \rho_{\mathrm{NAPL}})/\rho_{\mathrm{NAPL}}]\mathbf{g} \tag{7}$$

where $\mathbf{g}$ is the gravity vector and $\mathbf{F}_{\mathrm{NAPL}}$ is the force vector acting on the NAPL fluid. This equation illustrates how the density of the NAPL contributes to the magnitude and direction of its migration. This is particularly so when the hydraulic gradient of the water $\nabla\Phi_w$ is very small (as is likely at CRREL). For example, for TCE (ρ_{TCE} = 1.46 g/cm^3)

$$\mathbf{F}_{\mathrm{TCE}} = -0.68\,\nabla\Phi_w + 0.32\,\mathbf{g}.$$

If the groundwater gradient is 0.001, as it is near the Norwich well

$$\mathbf{F}_{\mathrm{TCE}} = -0.00068\,\mathbf{w} + 0.32\,\mathbf{g}$$

where $\mathbf{w}$ is the unit vector in the direction of groundwater flow. Thus, the subsurface movement of the contaminant is primarily downward. For large groundwater gradients, the TCE migration will also have a significant component of motion along the direction of groundwater flow.

However, capillary forces also influence the movement of the contaminant. These forces are a function of the interaction between the fluids and the soil grains and are characterized by the wetting angle and interfacial tension. The capillary forces act on the NAPL fluid according to the capillary equation, which can be written as an application of the Laplace equation for capillary tubes

$$P_c = p_{\mathrm{NAPL}} - p_w = \Delta\rho g h = 2\sigma\cos\Theta/r \tag{8}$$

where P_c = capillary pressure

Θ = contact angle, or the angle between the water and NAPL together in contact with the soil grain, as measured through the water

σ = interfacial tension between the two fluids

r = radius of the capillary tube

$\Delta\rho = \rho_{NAPL} - \rho_w$ = density of the NAPL minus density of the water

g = gravity

h = height of capillary rise

p_w = pressure of the water phase

p_{NAPL} = pressure of the NAPL phase.

The contact angle Θ is a measure of the wetting properties of the soil grains that are preferentially wet by different fluids, depending on the chemistry of the soil matrix and the natural groundwater. Saturated soil grains not previously exposed to organic contaminant fluids generally have contact angles less than 90° and are considered "water wet," although this may change with time as the chemistry of the system equilibrates. For these soils, water will adhere to the soil grains and the NAPL will remain isolated in the larger pore spaces. On the other hand, for soils that are NAPL wet (i.e., have a contact angle greater than 90°), as can occur when the unsaturated zone is fairly dry, the NAPL preferentially adheres to the soil grains.

A more practical form of the capillary equation can be obtained by substituting an effective pore size, approximated at 20% of the effective grain diameter d_{10}, for the capillary radius (i.e., $r = d_{10}/5$) and taking the gradient to get the impelling force $\mathbf{F}_c$ from capillary action

$$\mathbf{F}_c = -\text{grad}\ P_c/\rho_{NAPL} = (10\sigma \cos\Theta/\rho_{NAPL}\, d_{10}^2)\ \text{grad}\ d_{10}. \quad (9)$$

This equation demonstrates the effect of pore size on the NAPL movement. For example, when the soil has a small contact angle (i.e., preferentially water wet and $\cos\Theta$ is positive), the forces acting on the NAPL fluid will tend to move it toward the larger pore spaces (in the direction of increasing d_{10}). But if the soil has a large contact angle (preferentially NAPL wet and $\cos\Theta$ is negative), the NAPL fluid will be drawn into the fine-grained soils (in the direction of decreasing d_{10}). This phenomenon is illustrated by the laboratory experiments discussed later.

These equations for NAPL movement, along with the more familiar equations of solute transport, can be used to simulate subsurface contaminant migration. Such information is valuable for examining different spill scenarios and plume delineation for immiscible fluids.

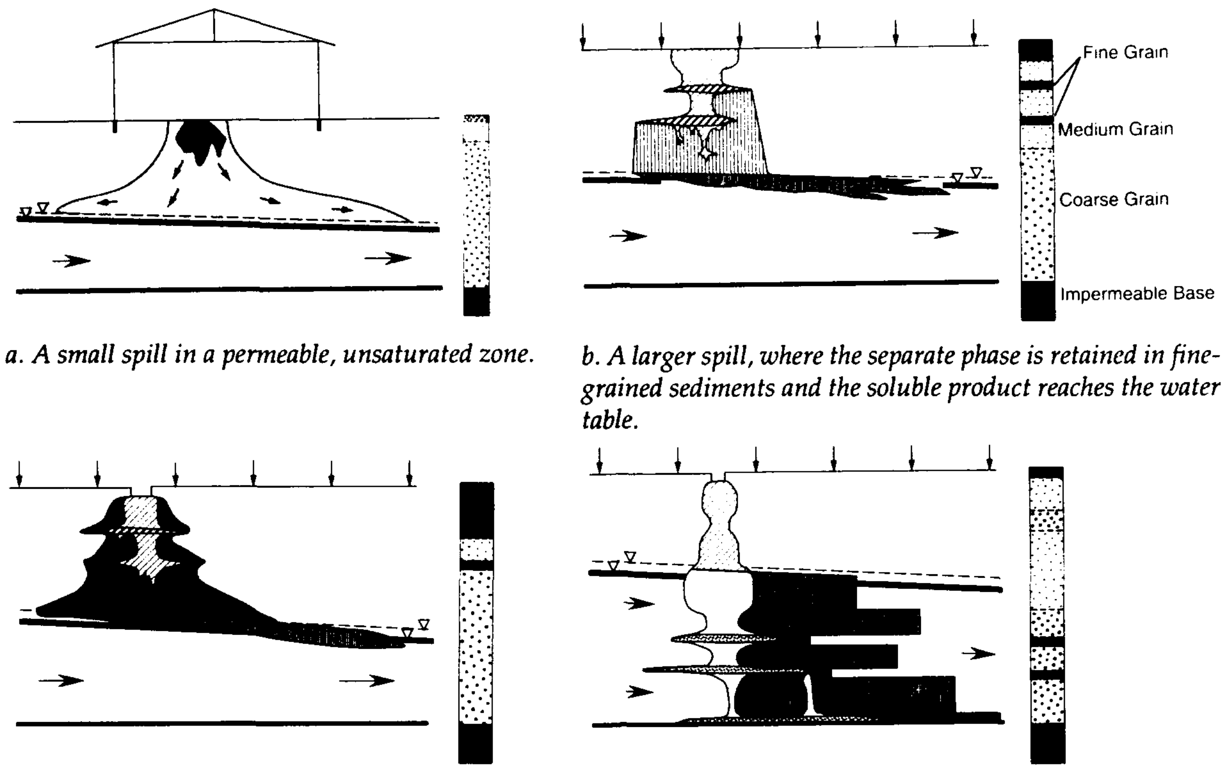
Experience with DNAPLs
(experiments and case studies)

Multiphase and immiscible fluid flow in porous media has been studied for a long time. In the past, much of the work has concentrated on the flow of petroleum products, an interest of the oil industry. The recent emphasis on contamination in groundwater, however, has increased the need for knowledge of the behavior of many other types of chemicals, including immiscible fluids with density greater than water (DNAPLs). TCE falls into this category.

In the 1970s a group of German researchers recognized the need for information on the spreading and migration of DNAPLs. They conducted many fine experiments that were published in German and later translated into English by Pankow (Schwille 1988). These experiments are the premier work in physical modeling of DNAPL movement under a variety of conditions. The work contains sketches and photographs of the DNAPL movement that are extremely useful for visualizing the behavior described by the equations above. For this reason, some of their results will be discussed briefly here.

Figure 32 shows schematics of plume development from various spills of a volatile chlorinated hydrocarbon. Each of the figures shows slightly different spill sizes and spill environments. These sketches were devised to represent the cumulative knowledge gained by the experiments of Schwille and his colleagues.

The figures are displayed in order of increasing spill size. Figure 32a shows a small spill in a dry and air-permeable soil. The DNAPL evaporates into a gas phase that sinks down to the capillary fringe of the water table and then spreads laterally. The gas phase moves with the air circulation in the soil. The spill depicted in Figure 32b is larger than that in Figure 32a, but still not large enough for the free-phase DNAPL to exceed the retention capacity of the unsaturated zone and penetrate the capillary fringe. The DNAPL collects on top of fine-grained soil layers with limited permeability where it may spread laterally if residual saturation levels are exceeded or by capillary action as indicated in eq 9. The presence of substantial water in these fine-grained soils exaggerates the lateral spreading. Precipitation and percolation through these



a. A small spill in a permeable, unsaturated zone.

b. A larger spill, where the separate phase is retained in fine-grained sediments and the soluble product reaches the water table.

c. Gas mound develops around a spill, similar in size to that in Figure 3b.

d. In large spills the separate phase moves through the groundwater and accumulates on an impermeable layer. The soluble product moves with the groundwater.

Concentration or Saturation		Concentration or Saturation	
High Low	Gas Phase	High Low	Residual Fluid Phase in Vadose Zone
High Low	In Aqueous Solution	High Low	As a Separate Fluid Phase Within Ground Water

Figure 32. Various spills of a volatile chlorinated hydrocarbon DNAPL (after Schwille 1988). A representation of the grain size of the medium is given on the right-hand side of each figure.

contaminated zones will then move the contamination solution down to the water table and into the groundwater. It will then flow in solution along with the groundwater flow. Figure 32c shows a vapor plume surrounding a spill similar in size to that in Figure 32b. The vapor is dense and sinks, building up over areas of lower permeability.

The last sketch (Fig. 32d) is of a spill that is large enough to exceed the retention capacities of both the unsaturated and saturated zones. The free phase fluid continues to sink until it reaches a confining layer, where it accumulates. The residual DNAPL in the sediments contaminates the groundwater by passing through it and the solution plume is carried with the groundwater flow. The solubilization of the residual free-phase product left in the soil pores will eventually clear the soil of the separate phase, given enough time and enough water moving through the soil. The free-phase pools of DNAPL on top of the confining layer will also solubilize, but even more slowly because the surface area in contact with the groundwater is smaller. However, because the solubility is so low, pools of free product would be removed faster by pumping the DNAPL directly rather than by trying to remove it in solution by flooding the soil with water.

Case studies on the behavior of TCE are also useful for understanding the subsurface behavior of the liquid. Figure 33 shows an idealized plume of a DNAPL such as TCE, compared to a Light Non-Aqueous Phase Liquid (LNAPL), like gasoline. Plume development and DNAPL migration from actual case studies are shown in Figures 34 and 35.

Figure 33. Spill migration behavior of a Light Non-Aqueous Phase Liquid (LNAPL) and a DNAPL.

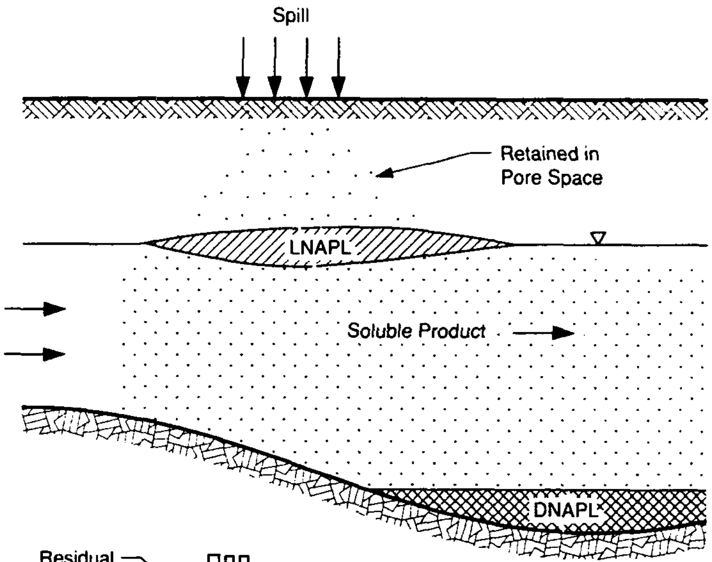


Figure 34. Case study sketch showing accumulation of a DNAPL in sub-topographic lows (after Nielsen, no date).

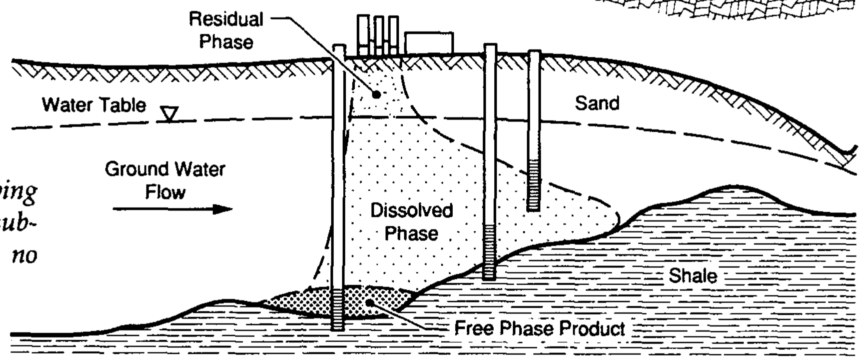


Figure 35. Migration of a dense leachate percolating to a perched water table (after Nielsen, no date).

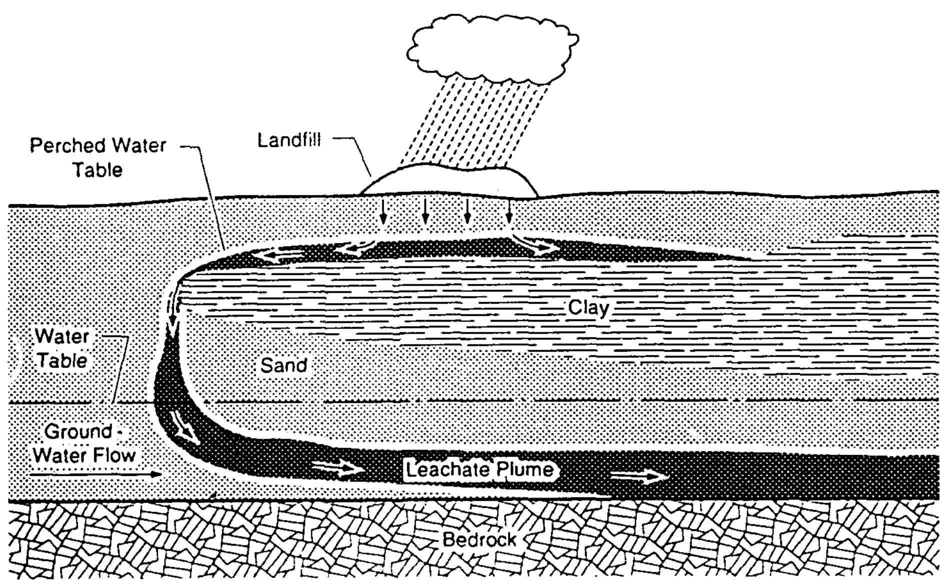


Figure 34 shows a case in which the TCE traveled down along the bedrock slope and pooled in a bedrock low area. Figure 35 illustrates how the vertical TCE movement may be controlled by and possibly perched above a low-permeability sediment layer.

SUMMARY AND CONCLUSIONS

In summary, TCE was discovered in three of the industrial wells at CRREL, as well as in two domestic wells in bedrock across the river. Figure 36, a plan view of the CRREL area, shows the locations

of the CRREL wells and the two wells across the river and their TCE levels. Well discharge rates are also shown for each of the wells, as these indicate the amount of use and the nature of the aquifer.

The geohydrology at CRREL can be separated into three hydrologic units—a high permeability esker deposit, lower permeability lake sediments and fractured bedrock. The esker is a high-yield aquifer that provides industrial water to CRREL from four wells. The pumping of these wells may induce groundwater recharge from the river.

The sketch in Figure 37 summarizes the geohydrology (known or estimated) at the CRREL site. It shows a cross section, similar to Figure 27, of the geohydrologic units, along with estimates of the hydraulic conductivity. Water level measurements are also shown.

TCE can migrate in the vapor phase, as a soluble component moving along with the groundwater, and as a separate or free phase. The free phase TCE leaves a residual portion retained on soil grains, particularly in fine-grained sediments and in the vadose zone. The mobile separate phase fingers down through the sediments layers seeking subtopographic lows.

In consideration of the above, small spills of TCE in the fine-grained soils at CRREL may not have exceeded the retention capacity of the soils and may remain as residual within the soil pores with a soluble component reaching the groundwater through infiltration. Larger spills may have passed through the saturated soil zone, seeking

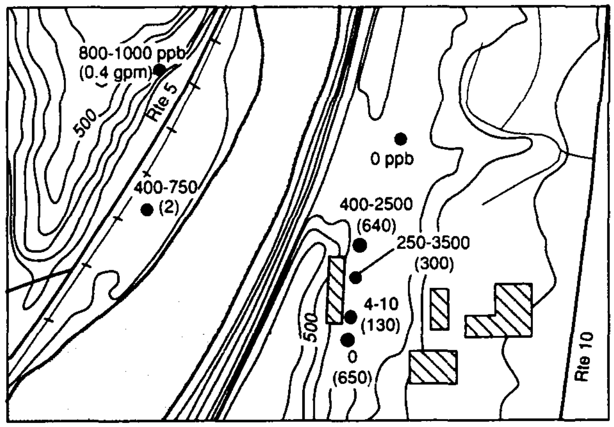


Figure 36. Well pump rates and TCE concentration of the CRREL wells, Hanover town well (not in current use) and the contaminated Vermont wells.

bedrock lows or continuing its downward movement along bedrock fractures. Since the CRREL wells may induce recharge from the river, the possibility of the contamination coming from that direction should not be overlooked.

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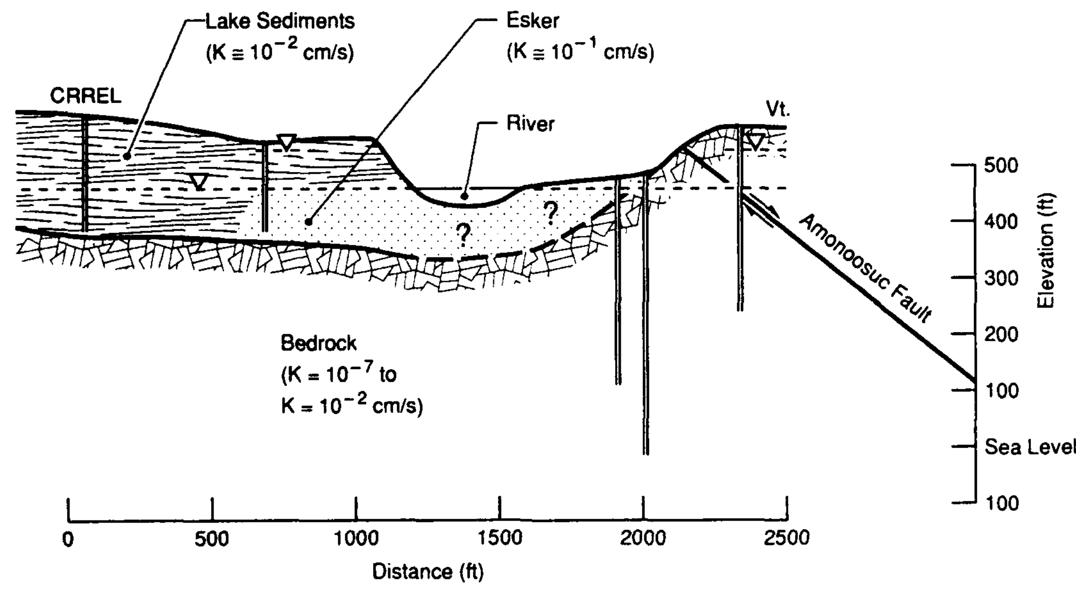

Figure 37. Geohydrological units labeled with approximate hydraulic conductivities. Groundwater levels (and perched water table measurements) are also shown.

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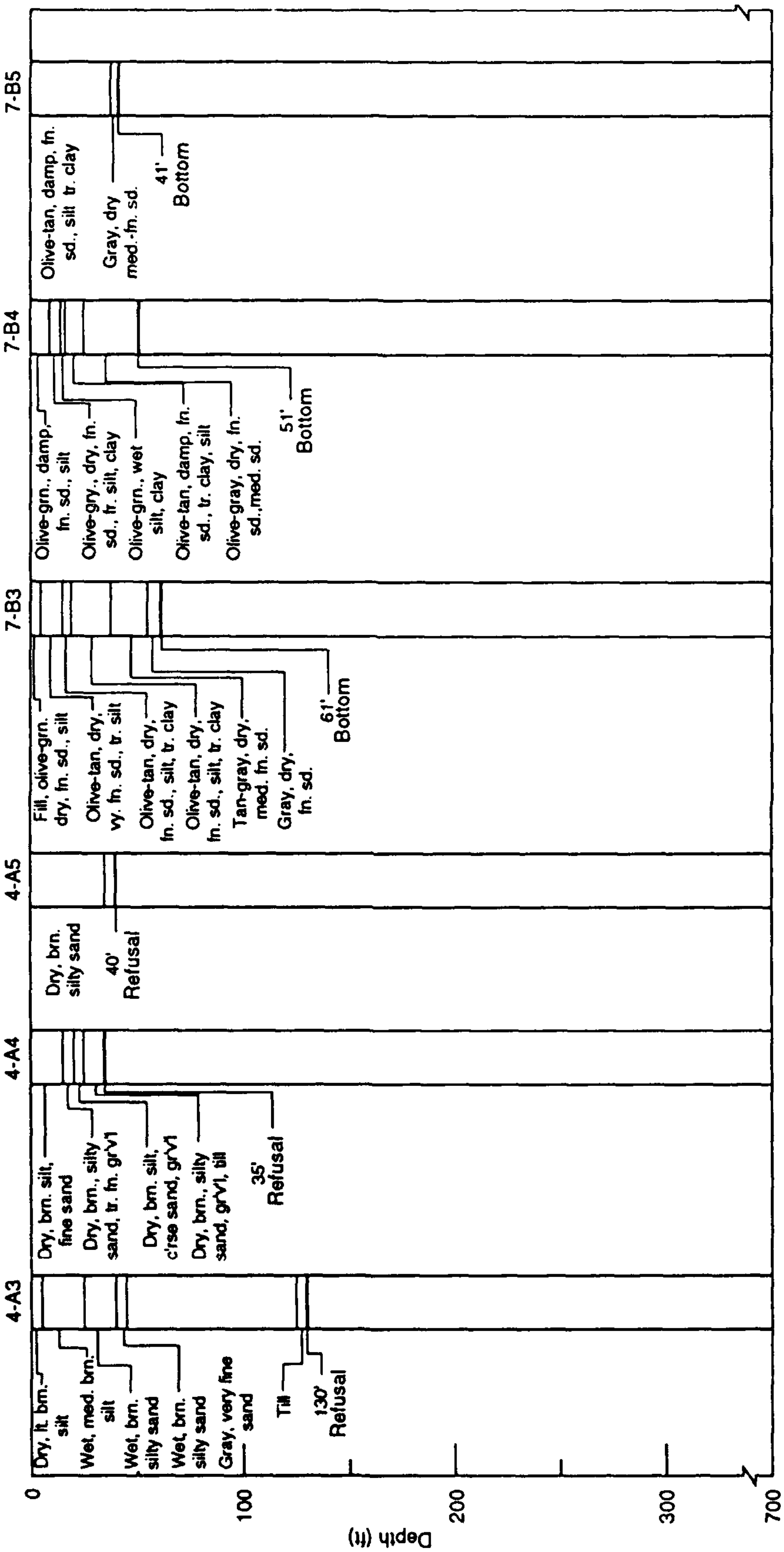
APPENDIX A: VERTICAL AERIAL PHOTOGRAPHS OF CRREL

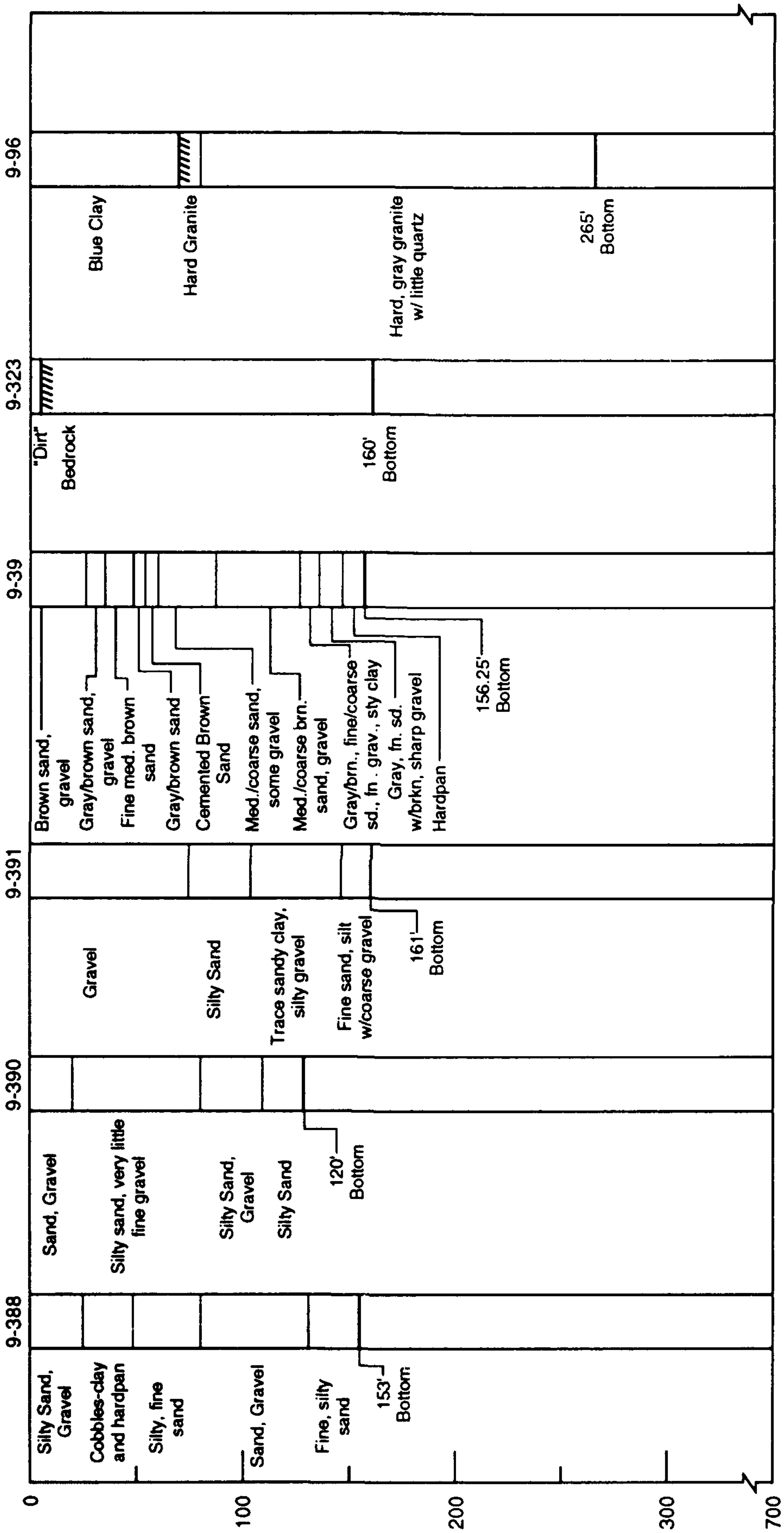
These photos are in CRREL's archives.
Additional oblique aerial photos are available from CRREL's Visual Information Branch.

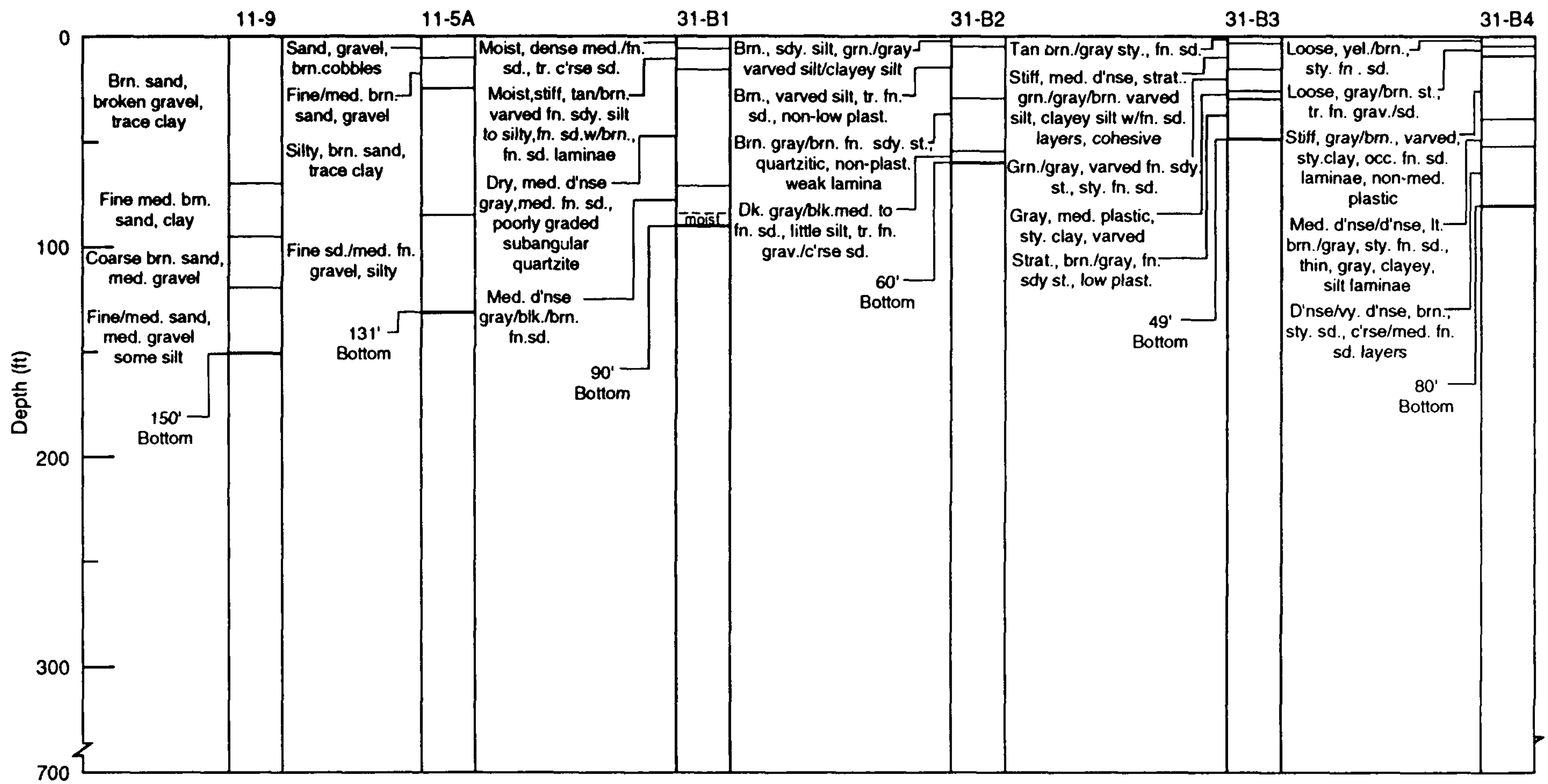
Date	*Approximate scale*	*Frame numbers*	*Film size (in.)*
5 Sep 75	1:5,000	20–22	9 × 9
5 Sep 75	1:5,000	13–16	9 × 9
5 Sep 76	1:5,000	17–19	9 × 9
4 Sep 75	1:5,000	85–87	9 × 9
9 Oct 66	1:16910	one frame not numbered	9 × 9
1969*	1:8450	107–111	7 × 7
1969*	1:8450	140–143	7 × 7
6 Oct 66	1:15,000	1-17, 1-18	9 × 9
8 Oct 66	1:7500	1-206 to 1-210	9 × 9
8 Oct 66	1:15,000	1-243 to 1-247	9 × 9
3 Feb 67	1:22,000	1-96, 1-98, 1-99	9 × 9
3 Feb 67	1:22,000	1-84 to 1-86	9 × 9
3 Feb 67	1:15,000	1-57 to 1-62	9 × 9
5 Oct 76	1:4,000	218–223	9 × 9
26 Apr 78	1:12,000	63–66	9 × 9
26 Apr 78	1:4,000	2–6	9 × 9
7 Aug 68	1:16,200	97–109	7 × 7
7 Aug 68	1:4,320	156–171	7 × 7
12 Sept†	1:2,180	37,39	9 × 9
12 Sept†	1:3,060	31–33	9 × 9
12 Sept†	1:1,030	33, 34, 36	9 × 9
14 Sep 76	1:3,000	66–68	9 × 9
15 Jul 76	1:11,000	239–241	9 × 9
29 Sep 75	1:5,200	285–287	9 × 9
5 Oct 76	1:2,800	224–227	9 × 9
5 Oct 76	1:3,000	230–232	9 × 9
6 Jun 78	1:4,800	39–43	9 × 9
9 Jul 76	1:4,000	179–181	9 × 9
5 Sep 75	1:6,000	23–26	9 × 9

* Specific date not given.
† Year not given.

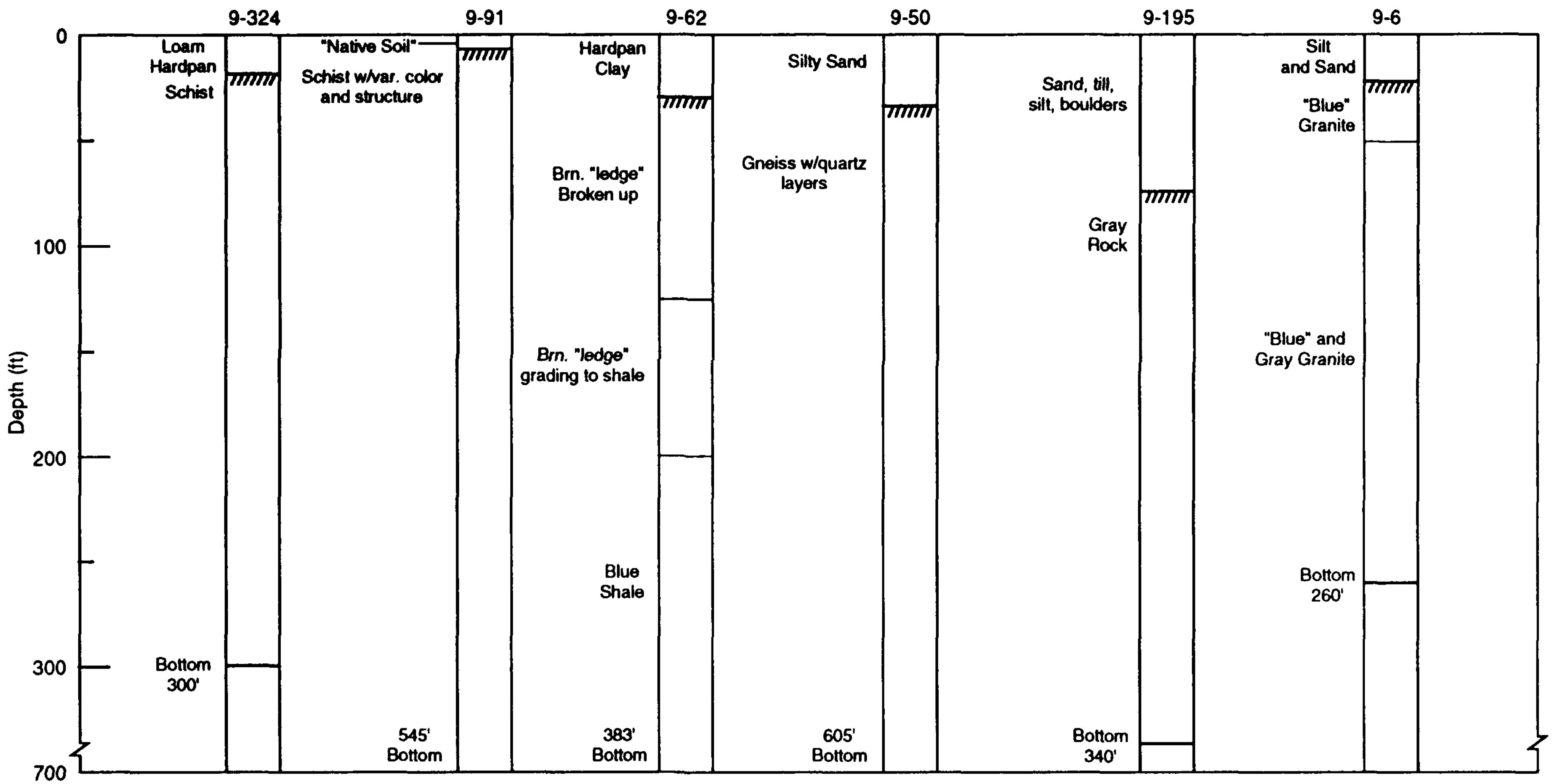
APPENDIX B: STRATIGRAPHY OF WELLS AND BORINGS IN THE CRREL AREA



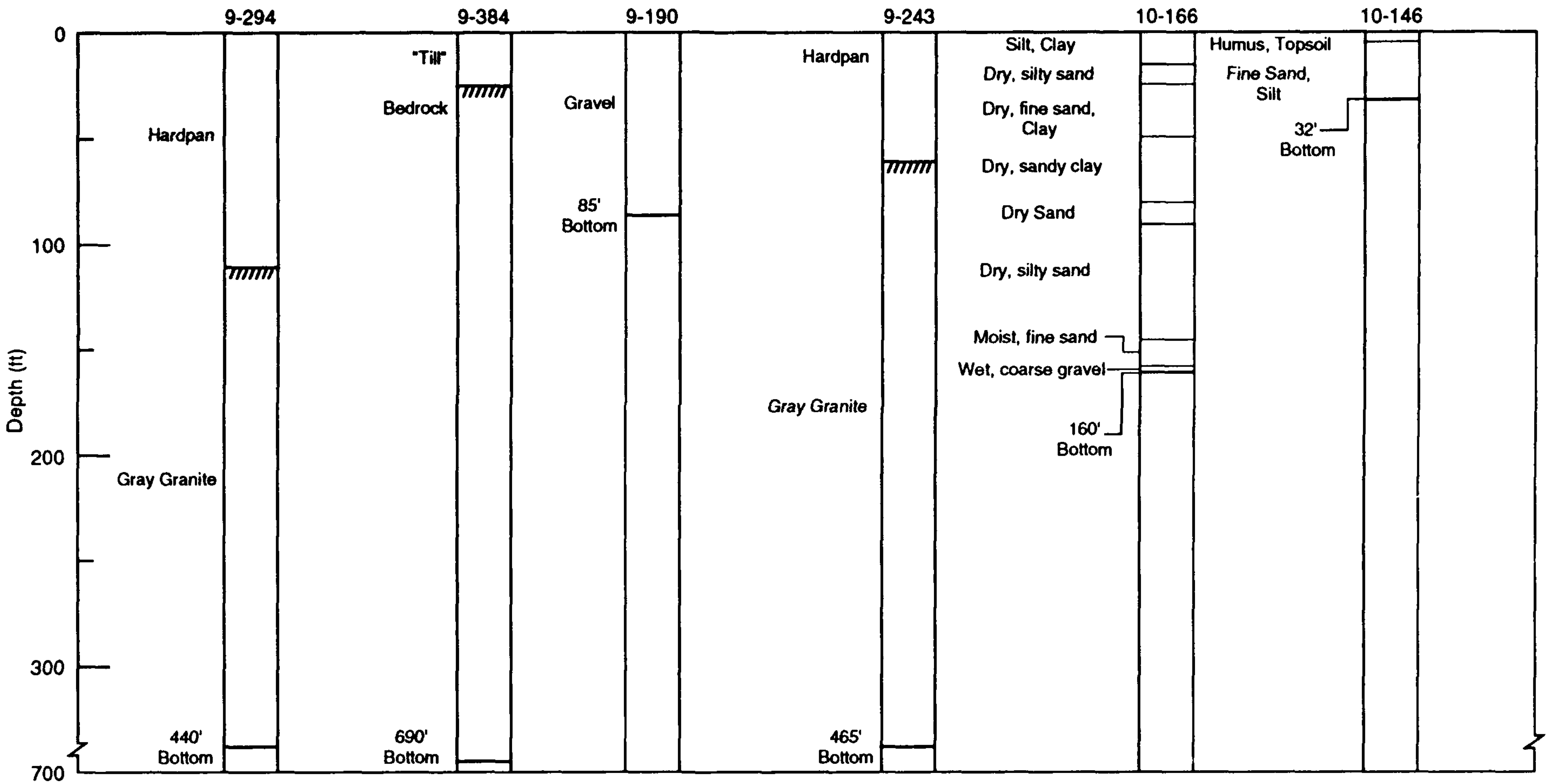

Depth (ft)
0
100
200
300
700
9-388
Silty Sand, Gravel
Cobbles-clay and hardpan
Silty, fine sand
Sand, Gravel
Fine, silty sand
153' Bottom
9-390
Sand, Gravel
Silty sand, very little fine gravel
Silty Sand, Gravel
Silty Sand
120' Bottom
9-391
Gravel
Silty Sand
Trace sandy clay, silty gravel
Fine sand, silt w/coarse gravel
161' Bottom
9-39
Brown sand, gravel
Gray/brown sand, gravel
Fine med. brown sand
Gray/brown sand
Cemented Brown Sand
Med./coarse sand, some gravel
Med./coarse brn. sand, gravel
Gray/brn., fine/coarse sd., fn. grav., sty clay
Gray, fn. sd. w/brkn, sharp gravel
Hardpan
156.25' Bottom
9-323
"Dirt"
Bedrock
160' Bottom
9-96
Blue Clay
Hard Granite
Hard, gray granite w/ little quartz
265' Bottom

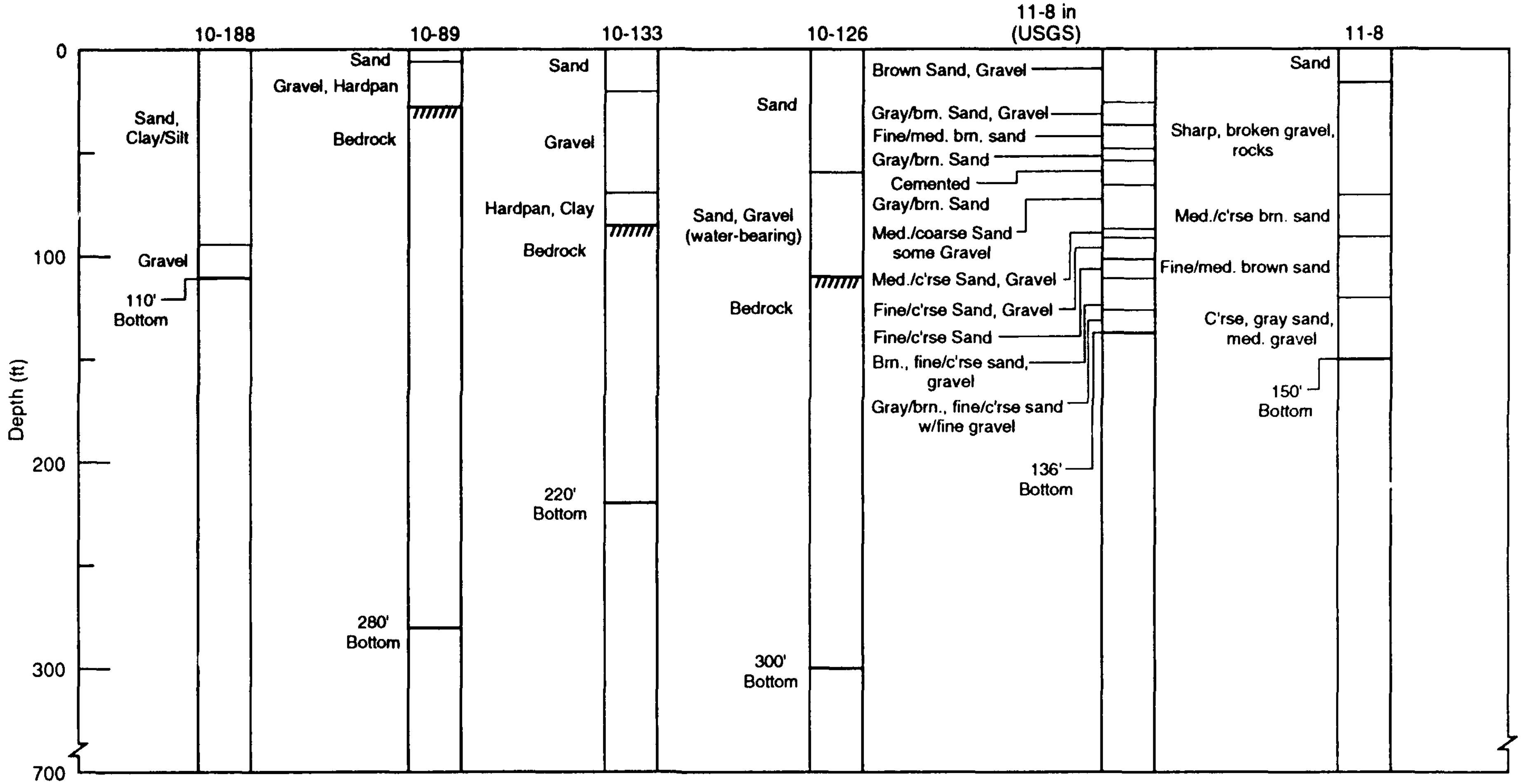


Depth (ft)
0
100
200
300
700
11-9
11-5A
31-B1
31-B2
31-B3
31-B4
Brn. sand, broken gravel, trace clay
Fine med. brn. sand, clay
Coarse brn. sand, med. gravel
Fine/med. sand, med. gravel some silt
150' Bottom
Sand, gravel, brn.cobbles
Fine/med. brn. sand, gravel
Silty, brn. sand, trace clay
Fine sd./med. fn. gravel, silty
131' Bottom
Moist, dense med./fn. sd., tr. c'rse sd.
Moist,stiff, tan/brn. varved fn. sdy. silt to silty,fn. sd.w/brn., fn. sd. laminae
Dry, med. d'nse gray,med. fn. sd., poorly graded subangular quartzite
Med. d'nse gray/blk./brn. fn.sd.
90' Bottom
moist
Brn., sdy. silt, grn./gray varved silt/clayey silt
Brn., varved silt, tr. fn. sd., non-low plast.
Brn. gray/brn. fn. sdy. st., quartzitic, non-plast. weak lamina
Dk. gray/blk.med. to fn. sd., little silt, tr. fn. grav./c'rse sd.
60' Bottom
Tan brn./gray sty., fn. sd.
Stiff, med. d'nse, strat. grn./gray/brn. varved silt, clayey silt w/fn. sd. layers, cohesive
Grn./gray, varved fn. sdy. st., sty. fn. sd.
Gray, med. plastic, sty. clay, varved
Strat., brn./gray, fn. sdy st., low plast.
49' Bottom
Loose, yel./brn., sty. fn . sd.
Loose, gray/brn. st., tr. fn. grav./sd.
Stiff, gray/brn., varved, sty.clay, occ. fn. sd. laminae, non-med. plastic
Med. d'nse/d'nse, lt. brn./gray, sty. fn. sd., thin, gray, clayey, silt laminae
D'nse/vy. d'nse, brn., sty. sd., c'rse/med. fn. sd. layers
80' Bottom

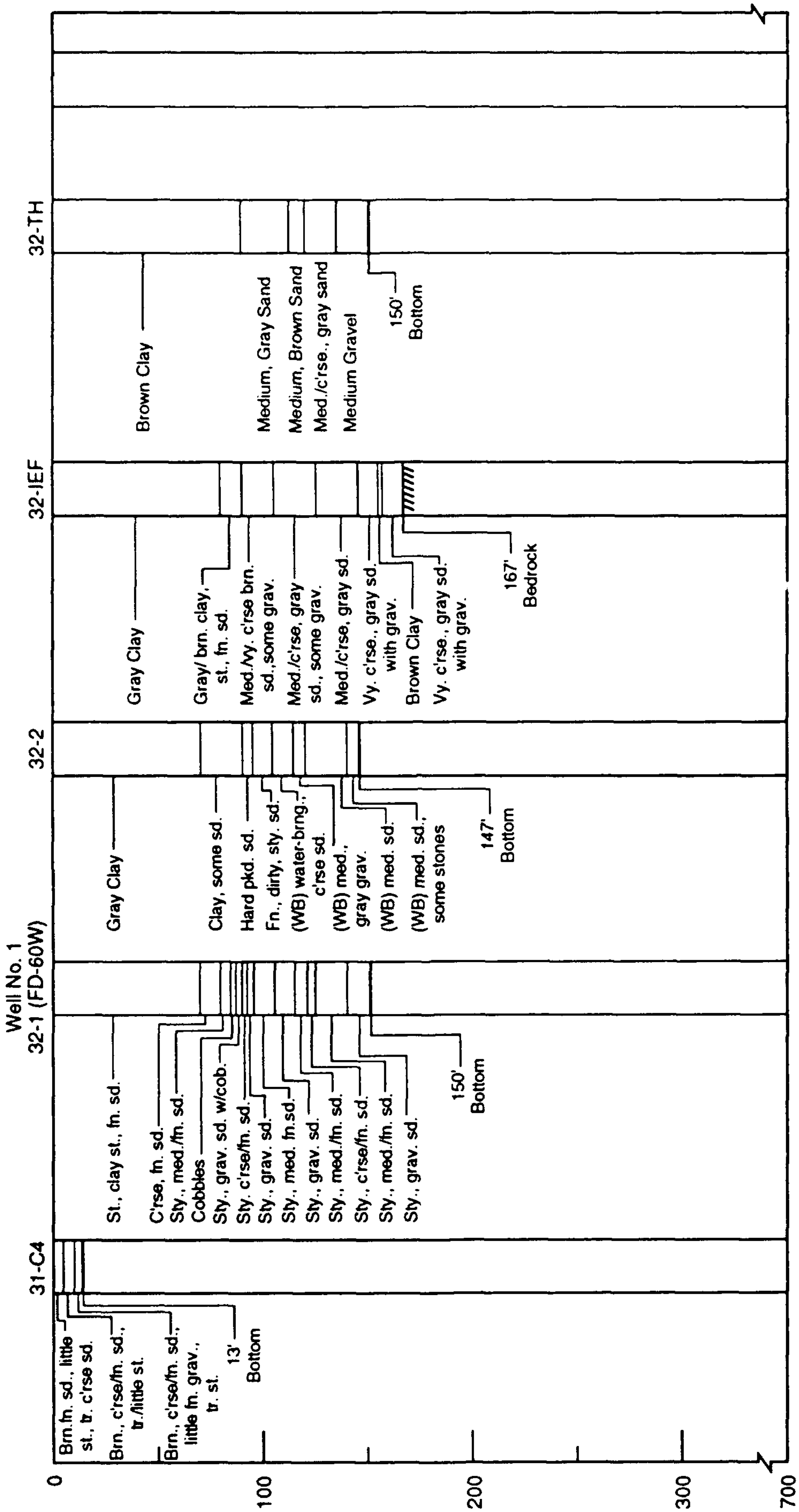


9-324
9-91
9-62
9-50
9-195
9-6
Depth (ft)
0
100
200
300
700
Loam
Hardpan
Schist
Bottom
300'
"Native Soil"
Schist w/var. color
and structure
545'
Bottom
Hardpan
Clay
Brn. "ledge"
Broken up
Brn. "ledge"
grading to shale
Blue
Shale
383'
Bottom
Silty Sand
Gneiss w/quartz
layers
605'
Bottom
Sand, till,
silt, boulders
Gray
Rock
Bottom
340'
Silt
and Sand
"Blue"
Granite
"Blue" and
Gray Granite
Bottom
260'

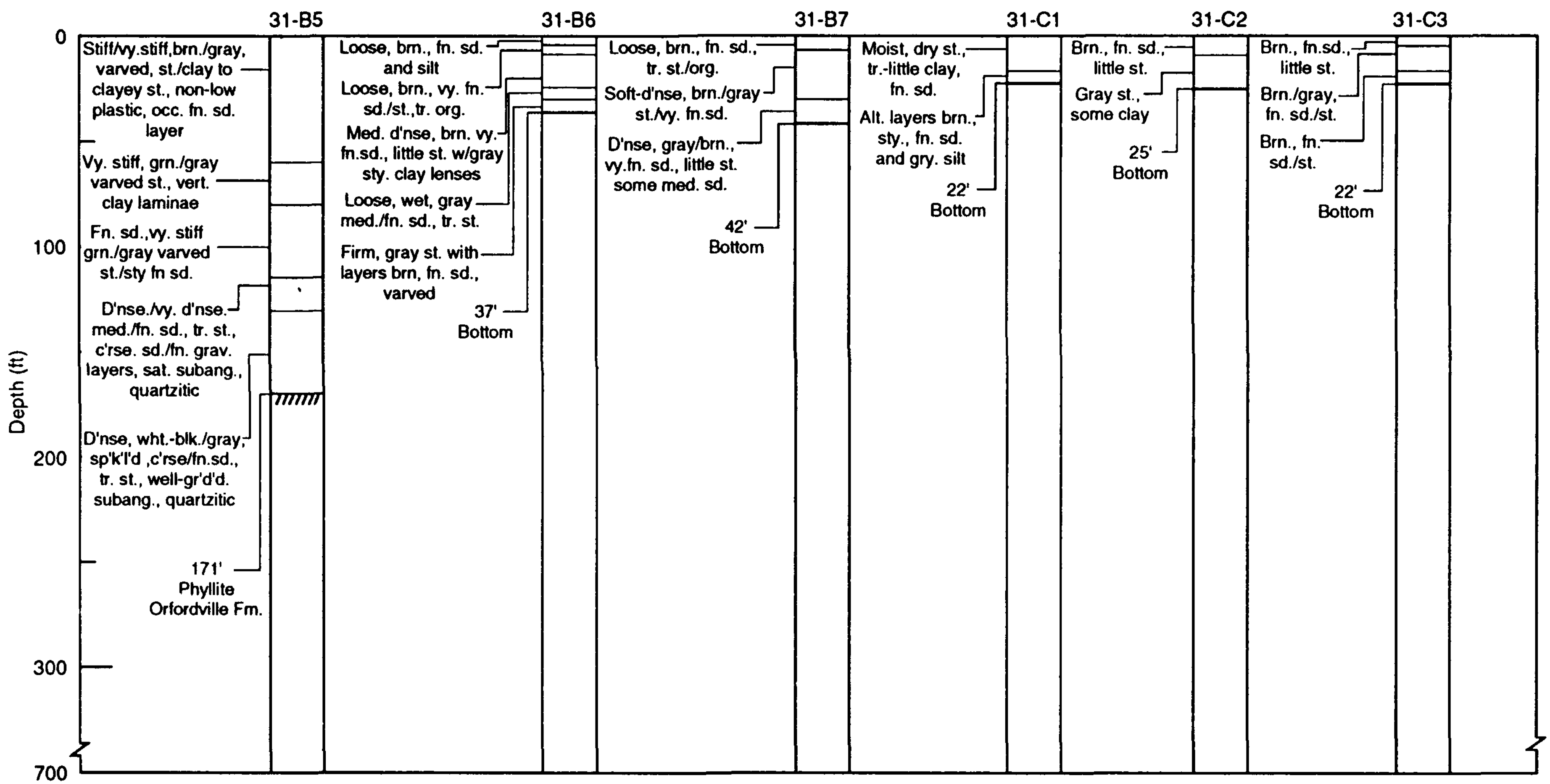

9-294
9-384
9-190
9-243
10-166
10-146
Depth (ft)
0
100
200
300
700
Hardpan
Gray Granite
440'
Bottom
"Till"
Bedrock
690'
Bottom
Gravel
85'
Bottom
Hardpan
Gray Granite
465'
Bottom
Silt, Clay
Dry, silty sand
Dry, fine sand,
Clay
Dry, sandy clay
Dry Sand
Dry, silty sand
Moist, fine sand
Wet, coarse gravel
160'
Bottom
Humus, Topsoil
Fine Sand,
Silt
32'
Bottom

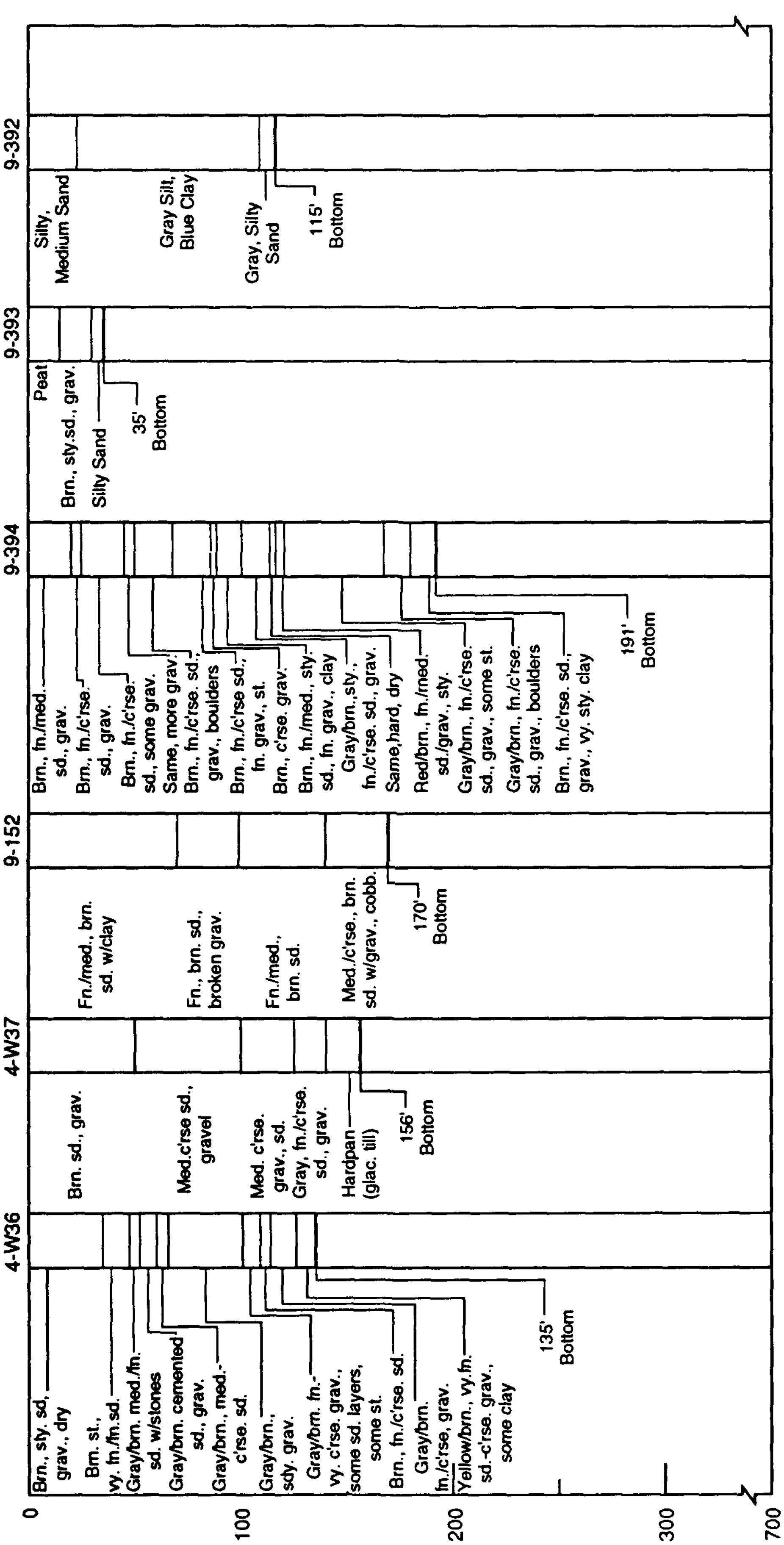


10-188
10-89
10-133
10-126
11-8 in (USGS)
11-8
Depth (ft)
0
100
200
300
700
Sand, Clay/Silt
Gravel
110' Bottom
Sand
Gravel, Hardpan
Bedrock
280' Bottom
Sand
Gravel
Hardpan, Clay
Bedrock
220' Bottom
Sand
Sand, Gravel (water-bearing)
Bedrock
300' Bottom
Brown Sand, Gravel
Gray/brn. Sand, Gravel
Fine/med. brn. sand
Gray/brn. Sand
Cemented
Gray/brn. Sand
Med./coarse Sand some Gravel
Med./c'rse Sand, Gravel
Fine/c'rse Sand, Gravel
Fine/c'rse Sand
Brn., fine/c'rse sand, gravel
Gray/brn., fine/c'rse sand w/fine gravel
136' Bottom
Sand
Sharp, broken gravel, rocks
Med./c'rse brn. sand
Fine/med. brown sand
C'rse, gray sand, med. gravel
150' Bottom



31-C4
Brn.fn. sd., little st., tr. c'rse sd.
Brn., c'rse/fn. sd., tr./little st.
Brn., c'rse/fn. sd., little fn. grav., tr. st.
13' Bottom
Well No. 1
32-1 (FD-60W)
St., clay st., fn. sd.
C'rse, fn. sd.
Sty., med./fn. sd.
Cobbles
Sty., grav. sd. w/cob.
Sty. c'rse/fn. sd.
Sty., grav. sd.
Sty., med. fn.sd.
Sty., grav. sd.
Sty., med./fn. sd.
Sty., c'rse/fn. sd.
Sty., med./fn. sd.
Sty., grav. sd.
150' Bottom
32-2
Gray Clay
Clay, some sd.
Hard pkd. sd.
Fn., dirty, sty. sd.
(WB) water-brng., c'rse sd.
(WB) med., gray grav.
(WB) med. sd.
(WB) med. sd., some stones
147' Bottom
32-IEF
Gray Clay
Gray/ brn. clay, st., fn. sd.
Med./vy. c'rse brn. sd., some grav.
Med./c'rse, gray sd., some grav.
Med./c'rse, gray sd.
Vy. c'rse., gray sd. with grav.
Brown Clay
Vy. c'rse., gray sd. with grav.
167' Bedrock
32-TH
Brown Clay
Medium, Gray Sand
Medium, Brown Sand
Med./c'rse., gray sand
Medium Gravel
150' Bottom
Depth (ft)
0
100
200
300
700


31-B5
31-B6
31-B7
31-C1
31-C2
31-C3
Depth (ft)
0
100
200
300
700
Stiff/vy.stiff,brn./gray, varved, st./clay to clayey st., non-low plastic, occ. fn. sd. layer
Vy. stiff, grn./gray varved st., vert. clay laminae
Fn. sd.,vy. stiff grn./gray varved st./sty fn sd.
D'nse./vy. d'nse. med./fn. sd., tr. st., c'rse. sd./fn. grav. layers, sat. subang., quartzitic
D'nse, wht.-blk./gray, sp'k'l'd ,c'rse/fn.sd., tr. st., well-gr'd'd. subang., quartzitic
171' Phyllite Orfordville Fm.
Loose, brn., fn. sd. and silt
Loose, brn., vy. fn. sd./st.,tr. org.
Med. d'nse, brn. vy. fn.sd., little st. w/gray sty. clay lenses
Loose, wet, gray med./fn. sd., tr. st.
Firm, gray st. with layers brn, fn. sd., varved
37' Bottom
Loose, brn., fn. sd., tr. st./org.
Soft-d'nse, brn./gray st./vy. fn.sd.
D'nse, gray/brn., vy.fn. sd., little st. some med. sd.
42' Bottom
Moist, dry st., tr.-little clay, fn. sd.
Alt. layers brn., sty., fn. sd. and gry. silt
22' Bottom
Brn., fn. sd., little st.
Gray st., some clay
25' Bottom
Brn., fn.sd., little st.
Brn./gray, fn. sd./st.
Brn., fn. sd./st.
22' Bottom



4-W36
4-W37
9-152
9-394
9-393
9-392
Depth (ft)
0
100
200
300
700
Brn., sty. sd., grav., dry
Brn. st., vy. fn./fn.sd.
Gray/brn. med./fn. sd. w/stones
Gray/brn. cemented sd., grav.
Gray/brn., med.-c'rse. sd.
Gray/brn., sdy. grav.
Gray/brn. fn.-vy. c'rse. grav., some sd. layers, some st.
Brn., fn./c'rse. sd.
Gray/brn. fn./c'rse, grav.
Yellow/brn., vy.fn. sd.-c'rse. grav., some clay
135' Bottom
Brn. sd., grav.
Med.c'rse sd., gravel
Med. c'rse. grav., sd.
Gray, fn./c'rse. sd., grav.
Hardpan (glac. till)
156' Bottom
Fn./med., brn. sd. w/clay
Fn., brn. sd., broken grav.
Fn./med., brn. sd.
Med./c'rse., brn. sd. w/grav., cobb.
170' Bottom
Brn., fn./med. sd., grav.
Brn., fn./c'rse. sd., grav.
Brn., fn./c'rse. sd., some grav.
Same, more grav.
Brn., fn./c'rse. sd., grav., boulders
Brn., fn./c'rse sd., fn. grav., st.
Brn., c'rse. grav.
Brn., fn./med., sty. sd., fn. grav., clay
Gray/brn.,sty., fn./c'rse. sd., grav.
Same,hard, dry
Red/brn., fn./med. sd./grav., sty.
Gray/brn., fn./c'rse. sd., grav., some st.
Gray/brn., fn./c'rse. sd., grav., boulders
Brn., fn./c'rse. sd., grav., vy. sty. clay
191' Bottom
Peat
Brn., sty.sd., grav.
Silty Sand
35' Bottom
Silty, Medium Sand
Gray Silt, Blue Clay
Gray, Silty Sand
115' Bottom

APPENDIX C: DETAILS OF HITCHCOCK SOIL SERIES (after Soil Conservation Service 1988)

T PIC oystrochrepts, coarse-silty, mixed, mesic

The Hitchcock Series consists of very deep well-drained soils that formed in silty lacustrine material. They are on level to very steep terraces or lake plains. Typically these soils have a brown silt loam surface layer 8 inches thick. The subsoil layers from 8 to 19 inches are light olive brown and light yellowish brown silt loam. The substratum from 19 to 60 inches is grayish brown or olive gray silt or silt loam. Slopes range from 0 to 60 percent.

Estimated Soil Properties (A)

Depth (in.)	USDA texture	Unified	AASHTO	Fract. > 3 in. (PCT)	Percent of material less than 3 in. passing sieve no 4	10	40	200	Liquid limit	Plasticity index
0–8	SIL, VFSL	ML	A–4	0	100	95–100	85–100	65–70	<35	NP-8
8–19	SIL, VFSL	ML	A–4	0	100	95–100	85–100	65–90	<35	NP-8
19–60	SI, SIL, VFSL	ML	A–4	0	100	95–100	85–100	65–100	<35	NP-8

Depth (in.)	Clay (PCT)	Moist bulk density (g/cm^3)	Permeability (in./hr)	Available water capacity (in./in.)	Soil reaction (pH)	Salinity (mμhos/cm)	Shrink–swell potential	Erosion factors K	Erosion factors T	Wind erod. group	Organic matter (PCT)	Corrosivity Steel	Corrosivity Concrete
0–8	3–10	1.00–1.30	0.6–2.0	0.18–0.30	4.5–6.5	—	Low	0.49	3	—	1–5	Low	Low
8–19	3–15	1.20–1.50	0.6–2.0	0.18–0.25	4.5–6.5	—	Low	0.49					
19–60	3–15	1.20–1.50	0.06–0.6	0.18–0.25	4.5–6.5	—	Low	0.49					

Flooding Frequency	Flooding Duration	Flooding Months	High-water table Depth (ft)	High-water table Kind	High-water table Months	Cemented pan Depth (in.)	Cemented pan Hardness	Bedrock Depth (in.)	Bedrock Hardness	Subsidence Init. (in.)	Subsidence Total (in.)	Hyd. group	Potential frost action
None			>6.0			—		>60		—		8	High

Sanitary facilities (B)	
Septic tank absorption fields	0–15%: Severe—Percs slowly 15+%: Severe—Percs slowly
Sewage lagoon areas	0–2%: Slight 2–7%: Moderate—Slope 7+%: Severe—Slope
Sanitary landfill (trench)	0–8%: Slight 8–15%: Moderate—Slope 15+%: Severe—Slope
Sanitary landfill (area)	0–8%: Slight 8–15%: Moderate—Slope 15+%: Poor—Slope
Daily cover for landfill	0–8%: Good 8–15%: Fair—Slope 15+%: Poor—Slope

Building site development (B)	
Shallow excavations	0–8%: Slight 8–15%: Moderate—Slope 15+%: Severe—Slope
Dwellings without basements	0–8%: Slight 8–15%: Moderate—Slope 15+%: Severe—Slope
Dwellings with basements	0–8%: Slight 8–15%: Moderate—Slope 15+%: Severe—Slope
Small commercial buildings	0–4%: Slight 4–8%: Moderate—Slope 8+%: Severe—Slope
Local roads and streets	0–15%: Severe—Frost action 15+%: Severe—Slope, frost action
Lawns, landscaping and golf fairways	0–8%: Slight 8–15%: Moderate—Slope 15+%: Severe—Slope

Regional interpretation

Construction material (B)	
Roadfill	0–15%: Fair—Low strength 15–25%: Fair—Slope, low strength 25+%: Poor—Slope
Sand	Improbable—Excess fines
Gravel	Improbable—Excess fines
Topsoil	0–8%: Good 8–15%: Fair—Slope 15+%: Poor—Slope

Water management (B)	
Pond reservoir area	0–3%: Slight 3–8%: Moderate—Slope 8+%: Severe—Slope
Embankments, dikes and levees	Severe—Piping
Excavated ponds, aquifer-fed	Severe—No water
Drainage	Deep to water
Irrigation	0–3%: Percs slowly, erodes easily 3+%: Percs slowly, slope, erodes easily
Terraces and diversions	0–8%: Erodes easily 8+%: Slope, erodes easily
Grassed waterways	0–8%: Erodes easily 8+%: Slope, erodes easily

Recreational Development (B)

Camp areas	0–8%: Moderate—Percs slowly 8–15%: Moderate—Slope, percs slowly 15+%: Severe—Slope	Playgrounds	0–2%: Moderate—Percs slowly 2–6%: Moderate—Slope, percs slowly 6+%: Severe—Slope
Picnic areas	0–8%: Moderate—Percs slowly 8–15%: Moderate—Slope, percs slowly 15+%: Severe—Slope	Paths and trails	0–15%: Severe—Erodes easily 26+%: Severe—Slope, erodes easily

Capability and Yields Per Acre of Crops and Pasture
(High-level management)

Class-determining phase	Capability		Corn silate (tons)		Alfalfa hay (tons)		Grass-legume-hay (tons)		Grass hay (tons)		Pasture (aum)					
	NIRR	IRR	NIRR	IRR	NIRR	IRR	NIRR	IRR	NIRR	IRR	NIRR	IRR	NIRR	IRR	NIRR	IRR
0–3%	1		26		4.5		4.5		4.5		8.5					
3–8%	2E		26		4.5		4.5		4.5		8.5					
8–15%	2E		22		4.0		4.0		4.5		7.5					
15–25%	4E		—		3.5		3.5		4.0		6.5					
25–35%	6E		—		—		—		—		—					
35+%	7E		—		—		—		—		—					

Woodland Suitability (C)

Class-determining phase	Ord. sym	Management problems: Erosion hazard	Equipment limit	Seedling mortality	Windth. hazard	Potential productivity: Plant competition	Common trees	Site index	Trees to plant
0–8%	30	Slight	Slight	Slight	Slight	Moderate	Sugar maple	65	Eastern white pine
8–15%	3R	Moderate	Slight	Slight	Slight	Moderate	East. white pine	75	Red pine
15–35%	3R	Severe	Moderate	Moderate	Slight	Moderate			White spruce
35+%	3R	Severe	Severe	Moderate	Slight	Moderate			Norway spuce

Windbreaks

Class-determining phase	Species	Height	Species	Height	Species	Height	Species	Height
	None							

Wildlife Habitat Suitability (D)

Class-determ. phase	Potential for habitat elements: Grain & seed	Grass & legume	Wild herb	Hardwood trees	Conifer plants	Shrubs	Wetland plants	Shallow water	Potential as habitat for: Openland wildlife	Woodland wildlife	Wetland wildlife	Rangeland wildlife
0–3%	Good	Good	Good	Good	Good	—	Poor	Very poor	Good	Good	Very poor	—
3–8%	Fair	Good	Good	Good	Good	—	Poor	Very poor	Good	Good	Very poor	—
8–15%	Fair	Good	Good	Good	Good	—	Very poor	Very poor	Good	Good	Very poor	—
15–25%	Poor	Fair	Good	Good	Good	—	Very poor	Very poor	Fair	Good	Very poor	—
25–35%	Very poor	Fair	Good	Good	Good	—	Very poor	Very poor	Fair	Good	Very poor	—
35+%	Very poor	Poor	Good	Good	Good	—	Very poor	Very poor	Poor	Good	Very poor	—

Potential Native Plant Community (Rangeland or Forest Understory Vegetation)

Common plant name	Plant symbol (NLSPN)	Percentage composition (dry weight) by class-determining phase				
Potential production (lb/actual dry weight): Favorable years Normal years Unfavorable years						

Footnotes:
A—Estimates of engineering properties based on test data from similar soils.
B—Ratings based on NSH Part II Section 403, March 1978.
C—Ratings based on National Forestry Manual, September 1980.
D—Ratings based on Soils Memo 74, January 1972.

Table C1. Engineering index properties.

Survey Area—Grafton County, New Hampshire

Map symbol	Soil name	Depth (in.)	Fragments > 3 inches (pct)	Percent passing–sieve number				Liquid limit (pct)	Plasticity index
				4	10	40	200		
130A	Hitchcock	0–8	0–0	100–100	95–100	85–100	65–90	15–35	0–8
		8–19	0–0	100–100	95–100	85–100	65–90	15–35	0–8
		19–65	0–0	100–100	95–100	85–100	65–100	15–35	0–8
130B	Hitchcock	0–8	0–0	100–100	95–100	85–100	65–90	15–35	0–8
		8–19	0–0	100–100	95–100	85–100	65–90	15–35	0–8
		19–65	0–0	100–100	95–100	85–100	65–100	15–35	0–8
130C	Hitchcock	0–8	0–0	100–100	95–100	85–100	65–90	15–35	0–8
		8–19	0–0	100–100	95–100	85–100	65–90	15–35	0–8
		19–65	0–0	100–100	95–100	85–100	65–100	15–35	0–8
130E	Hitchcock	0–8	0–0	100–100	95–100	85–100	65–90	15–35	0–8
		8–19	0–0	100–100	95–100	85–100	65–90	15–35	0–8
		19–65	0–0	100–100	95–100	85–100	65–100	15–35	0–8

Table C2. Physical and chemical properties of the soils.

Map symbol	Soil name	Depth (in.)	Clay (pct)	Moist blk. density (g/cm^3)	Permeability (in./in.)	Available water cap (in./in.)	Soil react. (pH)	Salinity (mμhos/cm)	Shrink–swell pot.	Erosion factor		Wind eros. group	Organic mat. (pct)
										K	T		
130A	Hitchcock	0–8	3–10	1.00–1.30	0.60–2.00	0.18–0.30	4.5–6.5	—	Low	0.49	3		1.0–5.0
		8–9	3–15	1.20–1.50	0.60–2.00	0.18–0.25	4.5–6.5	—	Low	0.49			0.0–0.0
		19–65	3–15	1.20–1.50	0.06–0.60	0.18–0.25	4.5–6.5	—	Low	0.49			0.0–0.0
130B	Hitchcock	0–8	3–10	1.00–1.30	0.60–2.00	0.18–0.30	4.5–6.5	—	Low	0.49	3		1.0–5.0
		8–19	3–15	1.20–1.50	0.60–2.00	0.18–0.25	4.5–6.5	—	Low	0.49			0.0–0.0
		19–65	3–15	1.20–1.50	0.06–0.60	0.18–0.25	4.5–6.5	—	Low	0.49			0.0–0.0
130C	Hitchcock	0–8	3–10	1.00–1.30	0.60–2.00	0.18–0.30	4.5–6.5	—	Low	0.49	3		1.0–5.0
		8–19	3–15	1.20–1.50	0.60–2.00	0.18–0.25	4.5–6.5	—	Low	0.49			0.0–0.0
		19–65	3–15	1.20–1.50	0.06–0.60	0.18–0.25	4.5–6.5	—	Low	0.49			0.0–0.0
130E	Hitchcock	0–8	3–10	1.00–1.30	0.60–2.00	0.18–0.30	4.5–6.5	—	Low	0.49	3		1.0–5.0
		8–19	3–15	1.20–1.50	0.60–2.00	0.18–0.25	4.5–6.5	—	Low	0.49			0.0–0.0
		19–65	3–15	1.20–1.50	0.06–0.60	0.18–0.25	4.5–6.5	—	Low	0.49			0.0–0.0

Table C3. Water features (survey area: Grafton County, New Hampshire).

Map symbol and soil name	Hydrologic group group	Flooding			High water table		
		Freq.	Duration	Months	Depth (ft)	Kind	Months
130A—Hitchcock	B	None		—	6.0–6.0		—
130B—Hitchcock	B	None		—	6.0–6.0		—
130C—Hitchcock	B	None		—	6.0–6.0		—
130E—Hitchcock	B	None		—	6.0–6.0		—

APPENDIX D: COMPOSITION OF AMMONOOSUC VOLCANICS

Table D1. Chemical analyses of pillowed greenstones and amphibolites (after Aleinoff 1977).

	H-1	H-2	H-3	H-4	H-5	H-7	M-8	M-10	M-11	M-12	M-13a	M-13b	M-14	M-15	M-17	M-3
SiO_2 (%)	51.49	52.06	53.31	51.54	52.93	50.29	56.94	51.13	49.65	50.96	49.55	48.54	52.24	50.52	46.50	47.93
TiO_2	2.01	2.29	2.36	1.42	1.64	2.08	0.51	1.08	0.90	0.93	1.02	0.95	2.32	2.26	0.93	1.34
Al_2O_3	14.60	15.19	14.79	17.74	17.09	15.31	15.40	15.15	15.53	17.78	17.69	18.45	16.73	15.52	14.77	18.20
FeO^*	10.90	11.38	11.49	9.50	8.63	8.99	8.78	10.28	10.43	9.72	9.28	9.26	10.63	10.32	7.86	11.16
MnO	0.20	0.18	0.21	0.16	0.18	0.15	0.14	0.17	0.16	0.14	0.11	0.13	0.19	0.19	0.14	0.12
MgO	4.94	4.31	4.53	5.56	5.02	3.95	4.32	5.00	4.76	4.98	4.80	4.86	5.16	5.15	4.72	4.55
CaO	11.69	8.57	9.49	9.96	10.23	12.05	8.12	10.82	11.52	10.57	12.96	13.07	10.35	11.55	15.07	8.80
Na_2O	2.93	3.26	3.55	3.79	3.51	3.87	2.51	3.13	2.57	3.16	2.82	2.83	2.95	2.26	3.17	2.54
K_2O	0.23	0.20	0.35	0.14	0.62	0.20	0.14	0.24	0.23	0.16	0.31	0.27	0.11	0.52	0.18	2.14
P_2O_5	0.40	0.16	0.35	0.25	0.22	0.35	0.20	0.42	0.21	0.13	0.29	0.28	0.22	0.16	0.13	0.45
H_2O^+	1.54	2.25	1.42	2.47	2.28	0.89	2.10	0.95	0.55	0.81	0.52	0.55	0.89	0.59	0.82	0.51
H_2O^-	0.13	0.17	0.13	0.13	0.13	0.14	0.20	0.16	0.10	0.13	0.10	0.09	0.13	0.13	0.14	0.19
$LOI^†$	0.64	0.49	0.59	0.78	0.15	3.14	0.66	1.94	2.75	1.23	2.58	2.24	1.01	1.08	6.19	2.55
Total	101.70	100.51	102.57	103.44	102.63	101.41	100.02	100.47	99.36	100.70	102.03	101.52	102.93	100.25	100.62	100.48
Ni (ppm)	56	62	47	70	69	52	64	126	133	47	55	51	72	61	50	107
Cr	43	44	38	60	49	41	58	84	81	52	50	55	43	47	46	66
Zr	137	126	171	120	128	170	48	50	47	52	51	57	156	150	47	60
Y	41	50	46	30	33	40	15	24	28	21	13	14	40	41	19	25
Sr	157	92	127	199	259	207	139	117	150	155	134	205	194	163	181	66
Rb	< 3	< 3	11.5	< 3	8	3	< 3	< 3	< 3	< 3	< 3	4	< 3	10	< 3	52

Note: Column headings are sample numbers.
* Total iron as FeO.
† Loss on ignition.

Table D2. Sedimentary and metasedimentary rocks, major constituents (%) (after Billings and Wilson 1965).

	1	2	3	4	5	6	7	8	9	10
SiO_2	61.52	66.26	60.49	32.36	9.46	57.50	73.12	58.14	58.92	64.33
TiO_2	0.64	0.48	n.d.	0.13	—	0.59	0.20	0.65	0.93	1.06
Al_2O_3	17.59	16.54	19.35	4.95	2.12	13.24	3.12	21.00	18.55	17.98
Fe_2O_3	1.54	1.42	0.48	—	—	0.51	0.34	0.33	0.94	1.41
FeO	4.86	3.53	5.98	0.71	0.15	3.68	1.68	6.32	6.63	4.80
MgO	2.76	2.76	2.89	3.55	9.16	4.86	3.90	3.41	3.24	1.19
MnO	0.04	0.09	n.d.	0.03	0.13	0.05	0.10	0.06	0.08	0.03
CaO	2.04	1.04	1.08	31.16	39.54	5.22	11.44	0.32	0.48	0.03
Na_2O	1.74	1.13	2.55	0.68	—	1.22	0.22	1.10	1.49	0.54
K_2O	3.55	3.22	3.44	0.84	0.12	3.49	1.55	3.85	3.74	3.49
H_2O^+	1.96	1.92	3.66*	0.13	0.08	2.33	0.40	4.47	3.90	3.90
H_2O^-	0.65	0.50							0.11	0.39
P_2O_5	tr	tr		—	—	0.03	—	—	0.14	0.11
S	0.49	0.11		—	—	—	0.04	0.09	0.17	0.03
CO_2	—	—		25.88	39.54	7.29	3.95	—	0.25	0.04
BaO				n.d.	n.d.	n.d.	n.d.	—	n.d.	0.05
F										
Cl										
ZrO_2								0.04		
C	0.87	0.98								0.44
	100.25	99.98	99.92	100.42	100.30	100.01	100.06	99.78	99.57	99.82
									−0.06†	
									99.51	

* Total H_2O.
† Less O for S.

1. Orfordville formation, mica schist, staurolite zone, $2\frac{1}{2}$ miles east–southeast of Piermont, Piermont township, Mt. Cube quadrangle.
2. Orfordville formation, staurolite–mica schist, staurolite zone, $1\frac{1}{4}$ miles east of Orford, Orford Township, Mt. Cube quadrangle.
3. Albee formation (?). Presumably a slate, listed as "argillyte" by Hitchcock, Woodsville, Woodsville quadrangle. Specimen probably from Bath Township.
4. Fitch formation, arenaceous dolomitic limestone, chlorite zone, Fitch Farm, $1\frac{1}{2}$ miles west–northwest of Littleton, Littleton Township, Littleton quadrangle.
5. Fitch formation, arenaceous dolomitic limestone, chlorite zone, four miles west of Littleton, Littleton Township, Littleton quadrangle.
6. Fitch formation, dolomitic slate, chlorite zone, $4\frac{1}{2}$ miles west–southwest of Littleton, boundary of Littleton and Lisbon Townships, Littleton quadrangle.
7. Fitch formation, diopside–actinolite granulite, staurolite zone, 1.15 miles north, 10 miles east of Garnet Hill, Lisbon Township, Moosilauke quadrangle.
8. Littleton formation, slate, chlorite zone, Slate Ledge Quarry, $2\frac{3}{4}$ miles west of Littleton, Littleton Township, Littleton quadrangle.
9. Littleton formation, slate, chlorite zone, Slate Ledge Quarry, $2\frac{3}{4}$miles west of Littleton, Littleton Township, Littleton quadrangle.
10. Little formation, black slate, $\frac{5}{8}$ mile west of Walker Mountain, Littleton Township, Littleton quadrangle.

Table D3. Sedimentary and metasedimentary rocks, trace elements (ppm) (after Billings and Wilson 1965).

	L65	L67	L70	L71	L73	L74	L75	L76	L77	L86
Ga	5.7	9.6	18	14	12	25	14	14	11	23
Cr	120	100	60	60	200	10	150	88	100	130
V	110	110	100	88	180	54	150	140	100	130
Li	tr*	71	59	—*	tr**	68	tr***	66	64	500
Ni	94	88	24	46	61	8.6	97	49	68	78
Co	40	20	14	20	20	—	27	16	17	18
Cu	13	31	33	82	16	3.4	9.5	10	1.1	4.8
Sc	10	17	7.8	7.6	16	25	8.1	6.4	9.9	12
Zr	210	250	110	130	150	370	220	150	300	150
Y	48	46	28	24	35	39	—*	29	30	24
Sr	690	550	560	340	1800††	800	930	1200	710	610
Pb	tr†	16	26	12	32	30	11	tr†	12	21

* Taken as 10 ppm for calculation.
† Taken as 5 ppm for calculation.
** Taken as 20 ppm for calculation.
†† Unreliable, are ignored for calculation.
*** Taken as 40 ppm for calculation.

Descriptions and locations of specimens from Littleton formation.

L65. Psammitic garnet schist, 2 miles west of Chesterfield on highway, Chesterfield Township, Brattleboro quadrangle.
L67. Garnet phyllite, $1\frac{1}{4}$ miles north from Westmoreland Depot, Westmoreland Township, Bellows Falls quadrangle.
L70. Sericite schist, Acworth, Acworth Township, Bellows Falls quadrangle.
L71. Sericite slate, 2 miles north from Claremont, Claremont Township, Bellows Falls quadrangle.
L73. Kyanite–garnet schist (Orfordville formation), 1 mile south–southeast from North Thetford, Lyme Township, Mt. Cube quadrangle.
L74. Feldspathic schist, $1\frac{1}{2}$ miles north from Lyme Centre, Lyme Township, Mt. Cube quadrangle.
L75. Psammitic garnet schist, 2 miles north from Mascoma, Hanover Township, Mascoma quadrangle.
L76. Garnet schist, 1 mile east from Mascoma, Lebanon–Enfield Township, Mascoma quadrangle.
L77. Garnet schist, 6 miles north–northwest from North Grantham, Route 10, Lebanon–Enfield Township, Mascoma quadrangle.
L84. Mica schist, Black Brook along Beech Hill trail, Easton Township, Moosilauke quadrangle.

Table D4. Volcanic and metavolcanic rocks, major constituents (%), exclusive of moat volcanics (after Billings and Wilson 1965).

	1	2	3	4	5	6	7	8	9
SiO_2	46.55	53.44	50.91	76.08	75.93	71.74	52.40	51.64	79.06
TiO_2	0.52	0.51	1.68	0.25	0.18	0.25	0.90	1.33	0.21
Al_2O_3	19.26	17.80	16.00	12.58	12.61	13.95	18.18	17.62	11.40
Fe_2O_3	2.58	3.11	1.17	0.59	0.21	0.85	—	1.14	0.60
FeO	9.73	6.18	8.81	1.22	1.13	1.38	5.59	7.80	0.60
MgO	6.67	6.24	6.85	0.42	0.58	1.16	6.26	7.74	0.09
MnO	0.25	0.12	0.21	0.03	0.03	0.06	0.10	0.12	tr
CaO	9.07	5.40	9.99	0.10	0.38	1.74	4.64	6.44	0.90
Na_2O	3.31	3.10	2.27	4.39	2.76	3.88	5.04	4.52	4.78
K_2O	0.09	0.26	0.69	3.75	5.87	2.38	0.58	0.25	1.40
H_2O^+	2.39*	4.00	0.97	0.33	0.21	1.35	3.84	1.29	0.47
H_2O^-			0.05	n.d.	0.01				
P_2O_5		0.11	0.20	0.05	0.02	0.05	0.19	0.09	—
S		0.03	0.03	0.02	0.02	0.15	—	tr	0.16
CO_2			0.07	—	—	1.00	2.13	—	0.51
BaO		n.d.	n.d.	n.d.	n.d.	n.d.	—	—	n.d.
F									
Cl									
ZrO_2		—	n.d.	n.d.	n.d.	n.d.	—	—	n.d.
C			n.d.		n.d.				
	100.42	100.30	99.90	99.81	99.94	99.93	99.85	99.98	100.18
			−0.01†		−0.01†				
			99.89		99.93				

* Total H_2O.
† Less oxygen for sulfur.

1. Orfordville formation, chlorite schist, Hanover Township, exact location unknown.
2. Ammonoosuc volcanics, chlorite–epidote schist, chlorite zone, 4 1/2 miles west from Littleton, Littleton Township, Littleton quadrangle.
3. Ammonoosuc volcanics, amphibolite, sillimanite zone, 3 1/2 miles west–southwest of Randolph, Randolph Township, Mt. Washington quadrangle.
4. Ammonoosuc volcanics, soda–rhyolite (fine-grained biotite gneiss), staurolite zone, Lisbon Township, 4 1/2 miles southwest of Littleton, Littleton Township, Littleton quadrangle.
5. Ammonoosuc volcanics, fine-grained biotite gneiss, 4 miles west–southwest of Randolph, Randolph Township, Mt. Washington quadrangle.
6. Ammonoosuc volcanics, schistose soda–rhyolite, chlorite zone, 5 miles west of Littleton, Littleton Township, Littleton quadrangle.
7. Volcanic member of Littleton formation,greenstone, chlorite zone, 2 1/2 miles west of Littleton, Littleton Township, Littleton quadrangle.
8. Volcanic member of Littleton formation, amphibolite, staurolite zone, Lisbon Township, 4 1/2 miles southwest of Littleton, Littleton Township, Littleton quadrangle.
9. Pebble in volcanic conglomerate member of Littleton formation, soda–rhyolite, chlorite zone, 3 miles west of Littleton, Littleton Township, Littleton quadrangle.

APPENDIX E: LOG OF SOIL BORING 31-B5

LOG OF BORING B-5 SHEET 1 OF 4

PROJECT AND LOCATION: Frost Effects Research Facility, CRREL, Hanover, N.H.		ELEVATION AND DATUM: 462 ft	PROJECT NO.: 78 C 527
DRILLING AGENCY: Granite State Explorations, N.H.	FOREMAN: Jeffrey Cushing	DATE STARTED: 10/2/1979 AM	DATE FINISHED: 10/4/1979
DRILLING EQUIPMENT: Speedstar Model SS-15-II Air Percussion Rig		COMPLETION DEPTH: 171' 8"	ROCK DEPTH: 170' 8"
SIZE AND TYPE OF BIT: 6 in. percussion	SIZE AND TYPE CORE BARREL: N. A	NO. SAMPLES: DIST. 12	UNDIST. 0 / CORE 0
CASING: (mud drilling)		WATER LEVEL (FT): FIRST 92 ft	COMPL. / 24 HR.
CASING HAMMER / WEIGHT: NA	DROP: NA	BORING ANGLE AND DIRECTION: Vertical	
SAMPLER: Standard 2in OD split spoon			
SAMPLER HAMMER / WEIGHT: 140 lbs/300 lbs	DROP: 30 in/12 in.	INSPECTOR: S.V. Nathan	

STANDARD PENETR. RESIST. BL/FT	DESCRIPTION	PIEZ.	DEPTH, FT	SAMPLES: TYPE NUMBER	SAMPLES: RECOV. FT	SAMPLES: PENETR. RESIST. BL/6 IN.	R. CORE: RECOVERY %	R. CORE: RQD	INDEX TESTS: W_n, %	INDEX TESTS: LL, %	INDEX TESTS: PL, %	INDEX TESTS: -200, %	REMARKS
	Topsoil (18in)		2										
	Stiff to very stiff brown-gray varved SILT to CLAYEY SILT (ML-CL). non-plastic to low-plastic, occasional thin fine sand layers (SM-SP)		4–38										175

LOG OF BORING B-5

SHEET 2 OF 4

STANDARD PENETR. RESIST. BL/FT	DESCRIPTION	PIEZ.	DEPTH, FT	SAMPLES TYPE NUMBER	RECOV. FT	PENETR. RESIST. BL/6"	R. CORE RECOVERY %	RQD	INDEX TESTS W_n, %	LL, %	PL, %	-200, %	REMARKS
	Stiff to very stiff brown-gray varved SILT / clayey SILT (ML-CL), low-plastic to non-plastic. occasional thin fine sand layers (SP-SM)		42										
			44										
			46										
			48										
			50										Sampling commenced at 60 ft.
			52										
			54										
			56										
			58										
64/6"	60 Very stiff green-gray varved SILT, vertical clay laminae (ML-CL)		60	S-1	1.2	12 20 44/6"							
			62										S-3 & S-4 very moist to wet samples
			64										
			66										
			68										
67	... ditto medium plastic (CL) ...		70	S-2	1.3	10 19 48							
			72										
			74										
			76										
	... ditto becoming at 81 ft.		78										
60/9"	81 FINE SAND, little SILT (SM)		80	S-3	1.2	4 25 35/12							
			82										Hole depth 90 ft
	Very stiff green-gray varved SILT / fine sandy SILT / silty FINE SAND (ML-SM)		84										
51			86	S-4	2.0	8 16 35 65			27.3		NP		10/3 o/n reading 4 ft of mud.
140	Dense to very dense brown green-gray silty fine SAND		88	S-5	1.3	22 56 84							S-5 very moist sample
			90										

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LOG OF BORING B-5 SHEET 3 OF 4

STANDARD PENETR. RESIST. BL/FT	DESCRIPTION	PIEZ.	DEPTH, FT	SAMPLES TYPE NUMBER	SAMPLES RECOV. FT	SAMPLES PENETR. RESIST BL/6IN.	R. CORE RECOVERY %	R. CORE RQD	INDEX TESTS W_n, %	INDEX TESTS LL, %	INDEX TESTS PL, %	INDEX TESTS -200, %	REMARKS
			94										S-6 through S-8 wet samples, probably saturated masked by too many fines (SILT, est. 30-35%)
66	Dense to very dense green-gray SILTY FINE SAND (SM)		96	S6	1.6	19 31 35			24.8			68.9	
			98										
105	becoming		100	S7	1.5	37 42 63							
	... ditto trace medium fine sand ...		102										
			104										
75	... ditto little medium fine sand, trace coarse sand - (SP-SM)		106	S8	1.5	19 31 44			23.6			54.0	Est. Water Table (Gut) enc. bet. 90 ft to 92 ft
			108										
			110										
	115		112										
			114										
114	Dense to very dense gray medium to fine sand, trace silt beg. brown in color. Saturated. Subangular, quartzitic (SP) Coarse sand & fine gravel. subangular. layer at 121 ft		116	S9	1.5	37 40 74			24.9			19.2	← Coarser, less silty & more pervious subsoils below 115 ft
			118										
			120										
			122										
			124										
57	Dense brown-gray medium to fine sand, trace (<5%) silt, little coarse sand (SW). Saturated. Subang. quartzitic		126	S10	1.4	19 26 31			20.2			13.1	
			128										
	131		130										← Distinct coarse grained speckle colored crevasse deposits filling below 131 ft
			132										
			134										
48	Dense white-black-gray speckled coarse to fine sand, trace silt, well-graded, subangular & quartzitic (SW)		136	S11	2.0	18 22 26 33 35			14.4			15.2	Saturated samples
			138										
			140										
			142										

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LOG OF BORING B-5 SHEET 4 OF 4

STANDARD PENETR. RESIST. BL/FT	DESCRIPTION	PIEZ.	DEPTH, FT	SAMPLES: TYPE NUMBER	SAMPLES: RECOV. FT	SAMPLES: PENETR. RESIST. BL/6IN.	R. CORE: RECOVERY %	R. CORE: RQD	INDEX TESTS: W_n, %	INDEX TESTS: LL, %	INDEX TESTS: PL, %	INDEX TESTS: −200, %	REMARKS
			146										
			148										
43	Dense well-graded white-black-gray speckled coarse to fine sand, little silt, subangular quartzitic (SW-SM)		150–152	S12	1.0	12, 21, 22			13.9			10	
			154–156			70, 56, 70							
			158–168										Installed $1\frac{1}{2}$ in. ID PVC to 137 ft. 2.5 ft stick-up
	Bedrock at 170'8"		170										
	Soft phyllite of Oxford-ville formation		172–194							178			Water Level Obs. Inside PVC: 10/4/79 AM: 12.5 ft PM: 12.5 ft 10/5/79 PM: 13.5 ft. 10/6/79 AM: 14.8 ft 10/9/79 AM: 15.0 ft Outside PVC (perched water) 10/4/79 AM: 3.5 ft 10/5/79 AM: 3.0 ft 10/8/79 AM: 3.0 ft 10/9/79 AM: 3.0 ft

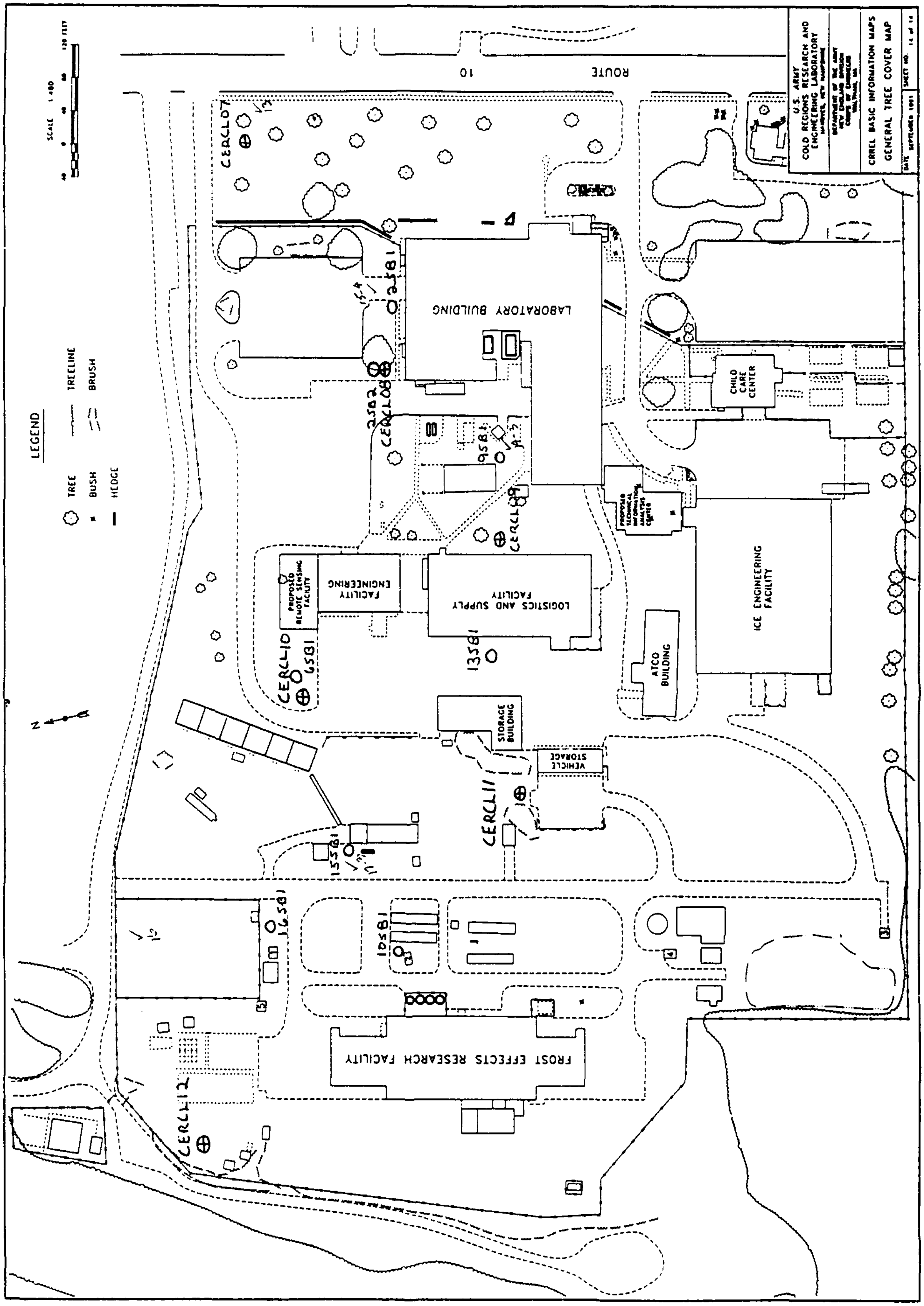
APPENDIX F: SELECTED DATA FROM CRREL WELLS AND BORINGS DRILLED DURING JANUARY AND FEBRUARY 1992 (from logs in Ecology and Environment [in press])

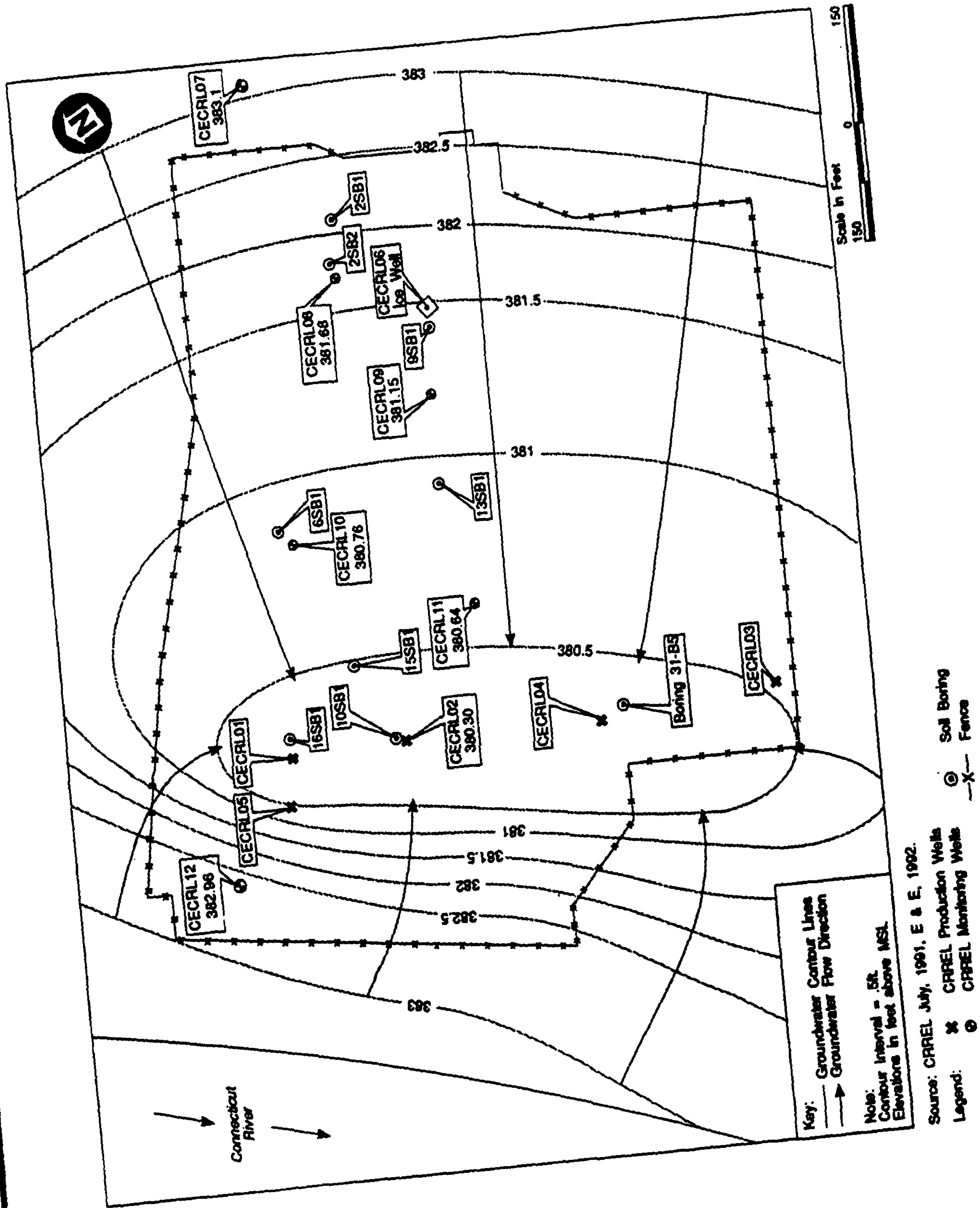
Well no.	*Total depth (ft)*	*Depth to bedrock (ft)*	*Est.* depth to sands (eksr) (ft)*	*Screened interval (ft)*	*Depth to water level while drilled (ft)*	*Depth to water level (April '92) (ft)*
Monitoring wells						
CECRL7	188.5	181	23	170–180	142	139.69
8	149	n.e.	99	137–147	133	131.02
9	139	n.e.	59.5	127–137	127	126.05
10	129	n.e.	?	117–127	112	112.34
11	118.5	n.e.	94.2	107–117	103.5 (20 perched)	95.86
12	100	62	0	78–98	85.2	84.84 (after completion)
Soil borings						
25 B1	45	n.e.	n.e.	nww	dry	dry
105 B1	10	n.e.	n.e.	nww	4	2
155 B1	35.5	n.e.	n.e.	nww	7	dry
165 B1	11.5	n.e.	n.e.	nww	dry	dry
95 B1	55	n.e.	n.e.	nww	dry	dry
25 B2	10.5	n.e.	n.e.	nww	dry	dry
65 B1	10.5	n.e.	n.e.	nww	dry	dry
135 B1	18.5	n.e.	n.e.	nnw	dry	dry

* Depth to sands estimated from change in sediment types on logs from CL or ML to SM or SP.

n.e.—not encountered.

nww—not a water well.


U.S. ARMY COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
CRREL BASIC INFORMATION MAPS
GENERAL TREE COVER MAP
LEGEND
TREE
BUSH
HEDGE
TREELINE
BRUSH
ROUTE 10
LABORATORY BUILDING
CHILD CARE CENTER
ICE ENGINEERING FACILITY
ATCO BUILDING
LOGISTICS AND SUPPLY FACILITY
ENGINEERING FACILITY
PROPOSED REMOTE SENSING FACILITY
STORAGE BUILDING
VEHICLE STORAGE
FROST EFFECTS RESEARCH FACILITY
CERCL07
CERCL08
CERCL09
CERCL10
CERCL11
CERCL12
2SB1
2SB2
9SB1
13SB1
6SB1
15SB1
10SB1
16SB1



CECRL07
383.1
383
382.5
2SB1
382
2SB2
CECRL06
Ice Well
381.5
CECRL08
381.68
9SB1
CECRL09
381.15
381
13SB1
6SB1
CECRL10
380.76
CECRL11
380.64
15SB1
380.5
Boring 31-B5
CECRL03
10SB1
16SB1
CECRL02
380.30
CECRL04
CECRL01
CECRL05
CECRL12
382.96
381
381.5
382
382.5
383
Connecticut River
Scale in Feet
150 0 150
Key:
Groundwater Contour Lines
Groundwater Flow Direction
Note:
Contour Interval = .5ft.
Elevations in feet above MSL
Source: CRREL July, 1991, E & E, 1992.
Legend:
CRREL Production Wells
CRREL Monitoring Wells
Soil Boring
Fence

BORING LOG GENERAL DATA

Project: CRREL Boring: CERCL07 Page: 1 of 6

Driller & Company: Mark PruehER

Geologist/Logger & Company: Robert Meyers Signature: Robert a Meyers

Date Boring Started: 1-28-92 Completed: 1 FEB 1992

Water Levels (from Ground Surface) Drilling Rig: ConTerra CT-250

First Encountered: Date:

While Drilling: Date:

At Boring Completion: 140 Date: 4 Feb 1992

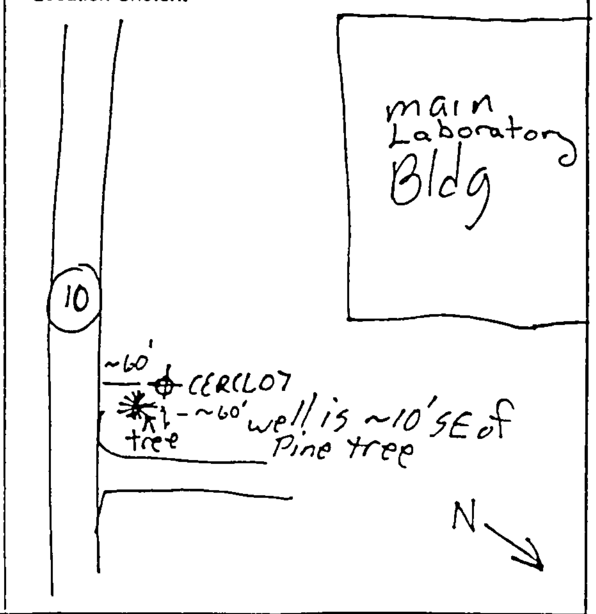
Drilling Shifts:

Date	Time Start	Time End	Depth of Drilling Per Shift Start	Depth of Drilling Per Shift End	Date	Time Start	Time End	Depth of Drilling Per Shift Start	Depth of Drilling Per Shift End
1-28-92	1425	1815	0'	100'					
1-29-92	0800	1744	100'	132'					
1-30-92	0800	1645	132'	150'					
1-31-92	0800	2015	150'	188.5'					
2-1-92	0800	1730	—	—					
2-2-92	0820								

Abbreviations:

Abbr.	Meaning
BGS	Below Ground Surface
R	Recovery
HNU	HNU MODEL 101 photoionizer (ppm)
S	Sample
2X	2" x 2' splitspoon

Location Sketch:



usagndat.pm4

BORING LOG GENERAL DATA
Borehole Number: CERCL07
Page: 1 of 6 Xerox: Sent to USATHAMA: 2/4/92
Signature: Robert a Meyers Date Sent:

58

BORING LOG GENERAL DATA
Borehole Number: CERLL07 Page: 2 of 6 Signature: Robert a Meyer Xerox: Sent to USATHAMA: 2 4 92 Date Sent:

59

Project: CRREL | Boring: CERLL07 | Page: 2 of 6

Depth/ Elevation (Ft.)	USCS Symbol/ Core Sketch	Soil/Rock Description	Sample Number & Depth	Blow Count & Recovery	Drilling Data
		GROUND SURFACE			
0'–3'	ml	0'-3' frozen brown silt loam			Note:1) All sampler driven by 140lb hammer w 30" FreeFall 2) All depths + recoveries in Feet 3) Depths From ground surface
3'–5'	ml	S-1, 3' to 5', SILT (100%) cohesive, non-plastic NO inclusions 5Y 5/2 100% Fines	S-1 3'-5' 2" R=0.8'	2 5 6 6	moist 4) Boring made using 9 7/8" open roller bit 1410 HNu = 0ppm
5'–8'	ml	Auger through same silt 5' to 8'			Note 0': 1) Drove 2x to 5' 2) Drove 2x 8' to 10' 3) Drove 2x 13' to 15' 4) Drove 2x 18' to 20'
8'–10'	ml	S-2, 8'-10' NO Recovery ~~5Y 5/2~~	S-2 8'-10 2" R=0.0'	8 9 6 6	1435 HNu = 0ppm
10'–13'	ml	Augered up the same silt Between 10' + 13'			
13'–15'	ml	S-3, 13'-15' SILT (100%) Cohesive, NON-plastic NO inclusions 1/4" Band of Limonitic staining 5Y 5/2 100% Fines	S-3 13'-15' 2" 1.4'=R	3 5 5 4	moist 1450 HNu=0ppm 0ppm H_2S 20.9% O_2 0% LEL
18'–20'	ml	S-4, 18'-20', SILT (99%) Same brown as above 1% clay band @ 19.6' BGS 5Y 5/2 100% Fines	S-4 18'-20' 2" R=1.5'	3 5 5 8	moist HNu=0ppm 1510

usagndat.pm4

Project: CRREL | Boring: CERCL 07 | Page: 3 of 6

Depth/ Elevation (Ft.)	USCS Symbol/ Core Sketch	Soil/Rock Description	Sample Number & Depth	Blow Count & Recovery	Drilling Data
		20' to 23' same SILT			
23'	Sm	S-5, 23'-25', VF sitly SAND (100%) Slightly Cohesive NONplastic 5Y 5/2 30% Fine sand 70% silt	S-5 2" 23'-25'	7 8 8 8	Slightly moist 1316 PID = 0.3ppm HNu = 0.3ppm Note: HNu originally read 60ppm but was not confirmed by PID or head space from geotechnical jar moments later.
25'			R=1.4'		
28'	Sm	S-6, 28'-30', VF silty SAND (99%), 1% gray clay layer @ 29.9' BGS NON-Cohesive, NON-plastic SAND, the clay is highly plastic & cohesive 5Y 4/2	S-6 2" 28'-30	7 8 8 10	moist @ bottom of split spoon. HNu = 0ppm PID = 0ppm 1531
30'			R=1.5'		5) Drove 2X 23'-25' 6) Drove 2X 28'-30' 7) Drove 2X 38'-40' 8) Drove 2X 48'-50'
38	SM Sm	S-7 38'-40' VF silty SAND (99%) with little clay Non plastic - NON Cohesive 5Y 4/2	S-7 38-40' 2"	8 8 8 12	Dry HNu = 0ppm PID = 0 ppm 1600
40 BT.			R=1.8		
48'	Sm	S-8, 48'-50', silty SAND (grayish brn) 48' to 48.5' was SILT with Limonitic staining (oxidation zone) 48.5' to 50', VF SAND, grayish brown, Non-cohesive, NON-plastic No inclusions 5Y 5/2	48'-50' S-8 2"	9 13 15 15	Dry HNu = Malfunction PID = 0ppm 1620 20.5% O_2 0ppm H_2S 0% LEL
50'			R=1.3'		

usagndat.pm4

BORING LOG GENERAL DATA
Borehole Number: CERCL07 | Page: 3 of 6 | Signature: Robert A. Myers | Xerox: | Sent to USATHAMA: 2/4/92 | Date Sent:

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BORING LOG GENERAL DATA

Borehole Number: CERCL07 Page: 4 of 6 Signature: Roberta Myer Xerox: Sent to USATHAMA: 2 FEB 92 Date Sent:

Project: CRREL			Boring: CERCL07		Page: 4 of 6
Depth/ Elevation (Ft.)	**USCS Symbol/ Core Sketch**	**Soil/Rock Description**	**Sample Number & Depth**	**Blow Count & Recovery**	**Drilling Data**
58'		VF. SAND Augered up			
58'	Sm	S-9, 58' to 60', VF Gray-Brn SAND NON-Cohesive NON-plastic no staining 5Y 5/2	S-9 2" 58'-60'	14 15 15 18 R=1.5'	moist $\boxed{1654}$ HNu is Malfunctioning PID = 0ppm
60'		*Probable Gravel Zone 64'-76'			Note: Slow drilling zone encountered @ 64' (till?) hard cuttings (maybe caused by
78'	Sm	S-10, 78'-80', F-M grained SAND (Brown) 100% non cohesive 5Y 3/2 non-plastic no staining or inclusions *Apparently not a gravel zone, the drilling is slow & difficult for no apparent reason.	S-10 2" 78'-80'	4 4 11 25 R=1.2'	$\boxed{1811}$ moist PID=0ppm rig problems) 9) Drove 2X 58'-60' 10) Drove 2X 78'-80'
80'		Same SAND			11) Drove 2X 98'-100'
98'	Sm	S-11, 98'-100', Same as above, 100% F-M grained SAND, non-plastic, non-cohesive, does have single 1/8" oxidation band. 5Y 3/2	S-11 2" 98'-100'	15 12 13 11 R=1.4'	$\boxed{1938}$ PID=10ppm moist 12) Drove 2X 118'-120' END 28JAN1992
100'		Same SAND			BEGIN 29JAN1992
118'	Sm	S-12, 118'-120', F-M grained SAND, dark brown non-plastic non-cohesive no inclusions no staining 5Y 4/2	S-12 2"	24 32 27 28 R=1.5'	$\boxed{1611}$ PID = 0ppm HNu = 0ppm Moist
120'					

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BORING LOG GENERAL DATA
Borehole Number: CERCL07
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Signature:
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Project: UC 3050 CRREL			Boring: CERCL07	Page: 5 of 6	
Depth/ Elevation (Ft.)	USCS Symbol/ Core Sketch	Soil/Rock Description	Sample Number & Depth	Blow Count & Recovery	Drilling Data
130 – 132	Sm	S-13, 130' to 132', brown F-M grained SAND no staining non-cohesive, non-plastic 5Y 4/2	S-13 2" 130-132	8 40 21 27, R = 1.5'	13) Drove 2X 130'-132' HNU = 0ppm PID = 0ppm 1717 END 1/29/92
132 – 142		✓ Water (prior to development) H_2O			BEGIN 1/31/92 Note 150':
150 – 152	Sp	S-14 150 to 152' F-M Grained Sand non plastic F-50% non cohesive M-50% no staining Very Moist but not saturated 5Y 3/2	S-14 2"	18 21 24 26 R = 1.3	1) Drove 2X 150'-152' 2) Drove 2X 158-160' 10:00 HNU = 0ppm PID = 0ppm End 1/31/92
158 – 160	Sp	Medium to Coarse-grained sand Med - 75% Coarse - 25% non cohesive 5Y 3/2 non plastic Saturated at bottom remainder is wet	S-15 2"	21 23 22 24 R = 1.0	3) Drove 2X, 165.5-167.5' 11:45 HNU = 0ppm PID = 0ppm very moist to wet
160 – 165.5		↑ cuttings included Large sand ↓ grains and clay (all Gray)			
165.5 – 167.5	Sm	S-16, 165.5' to 167.5', 60% VF Gray SAND, 40% Gray silt non-cohesive, non-plastic no staining or inclusions N5 (medium gray)	S-16 2" 165.5 to 167.5'	19 36 37 44 R = 0.8	very moist to wet 1300 HNU = 0ppm PID = 0ppm

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BORING LOG GENERAL DATA

Borehole Number: CERCL 07

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Sent to USATHAMA: 2/4/92

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Xerox:

Signature:

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Project: VC-30550 CRREL			Boring: CERCL07		Page: 6 of 6
Depth/ Elevation (Ft.)	USCS Symbol/ Core Sketch	Soil/Rock Description	Sample Number & Depth	Blow Count & Recovery	Drilling Data
174.5		S-17 174.5 - 176.5		35	4) Drove 2x 174.5-176.5
	Sm	Very Fine Gray Sand 50% VF sand 50% silt moist at top 6" Maybe wet at bottom 3" non cohesive non plastic no inclusions N5 (medium gray)	S-17 2"	50	5) Switched to 9 7/8" Solid tricone bit at 181 14:11 HNU = 0ppm PID = 0ppm
176.5				R=.9'	6) Mud loss at ~183'. 7) Drilled to 186' could not maintain circulation 8) Pulled Drill rod END 31 JAN 1992
181		Top of Bedrock @ 181' BGS Bedrock is phyllite of the Orfordville Formation			BEGIN 2/1/92 Note 1) Hole had sluffed to above bedrock overnight 2) Hole redrilled to 182' + rods pulled 3) Bentonite plug 180'-182' 4) 4" well w/ 10' screen will be installed above plug. 5) Water level at 142' BTOC on 4 Feb 1992 prior to development END 1 FEB 1992

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BORING LOG GENERAL DATA

Project: CRREL Boring: CERCL12 Page: 1 of 5

Driller & Company: Mark Prucher (WTD) Environmental

Geologist/Logger & Company: Bob Meyers (E+E) Signature: Robert A Meyers

Date Boring Started: 1-21-92 Completed:

Water Levels (from Ground Surface) Drilling Rig: Cat Tract-250

First Encountered: 88.3' (only in replacement hole) Date: 1-24-92

While Drilling: Unable to obtain Date:

* abandoned first drilling location for CERCL12, hole collapsed after augers removed

* Auger Refusal @ ~65' BGS

At Boring Completion: 45' BGS Date: 1-27-92

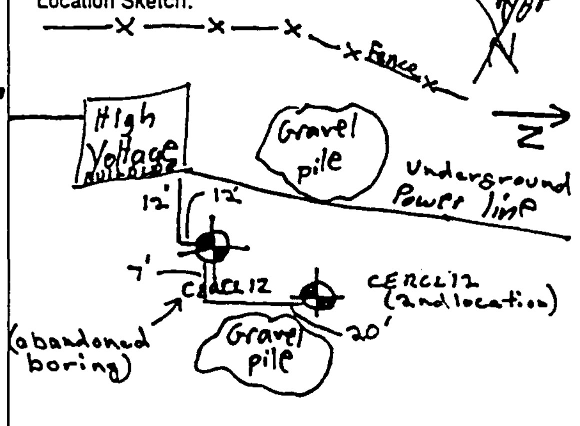
Drilling Shifts:

Date	Time		Depth of Drilling Per Shift		Date	Time		Depth of Drilling Per Shift	
	Start	End	Start	End		Start	End	Start	End
1-21-92	0800	~1800	*0' BGS	*65'					
1-22-92	0730	1735	0'	72'					
1-23-92	0730	1745	72'	100'					
1-24-92	0725	1733	100'	100'					
1-25-92	0728	2015	100'	100'					

Abbreviations:

Abbr.	Meaning
BGS	Below Ground Surface
HNU	HNU MODEL 101 Photoionizer
PID	Photoionizing Detector (Photovac Microtip)
S	Sample
2X	2" x 2' Splitspoon
$\boxed{0340}$	Sample time
R	Recovery

Location Sketch:



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Project: CRREL | Boring: CERCL12 | Page: 2 of 5

Depth/ Elevation (Ft.)	USCS Symbol/ Core Sketch	Soil/Rock Description	Sample Number & Depth	Blow Count & Recovery	Drilling Data
		GROUND SURFACE			Began 0844
2.5'		S1, 2.5' to 4.5' 2.5' to 3.1' VF to Coarse SAND with some silt + Trace Gravel 3.1' to 4.5' Gray SILT with trace Gravel 5Y 5/2 Cohesive, non-plastic 75% Sand 20% Silt 5% Gravel	S1 2" 2.5'-4.5' R=	16 15 15 12 2.0'	$\boxed{0908}$ HNU = 0 ppm PID = 0 ppm Dry Note: 1) Samples driven by 140 lb Hammer w/ 30" Free Fall 2) Depths and recoveries in Feet 3) Depths From ground surface
4.5'		4.5' to 7.5' Augered up SILT and rounded Cobbles/pebbles			
7.5'		S2, 7.5' to 9.5', Brown SILT with some VF to Coarse sand and Gravel. Angular to rounded and a single rounded cobble. cohesive, Non-plastic 5Y 3/2 80% Silt 20% Sand + Gravel	S2 2" 7.5'-9.5' R=	6 9 15 17 0.8'	$\boxed{0920}$ HNU = 0 ppm PID = 0 ppm Dry 4) Sampler driven inside 6¼" hollow stem auger
9.5'		~~9.5' to 12.5' silt + cobbles~~			Note 0': 1) 2X driven 2.5 to 4.5' (Frozen ground)
12.5'		S3, 12.5' to 14.5' VF to Coarse SAND with silt and rounded pebbles 60% Sand 5Y 6/1 5% Silt 35% Pebbles + Small Cobbles	S3 2" 12.5'-14.5' R=	3 9 11 15 0.6'	$\boxed{0929}$ HNU = 0 ppm PID = 0 ppm DRY 2) Drove 2x 7.5'-9.5' 3) Drove 2x 12.5'-14.5' 4) Drove 2x 17.5'-19.5 (no recovery)
14.5' 17.5'		S-4 17.5-19.5 No Recovery moist silt on tip of spoon	S4 2" 17.5'-19.5 R=	14 27 33 40 0.0'	HNU = 0 ppm PID = 0 ppm moist $\boxed{0952}$
19.5'					

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BORING LOG GENERAL DATA
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Sent to USATHAMA: 2/3/92
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BORING LOG GENERAL DATA
Borehole Number: CERCL12
Page: 3 of 5 Xerox: ______ Sent to USATHAMA: 2/3/92
Signature: Robert A. Myers Date Sent: ______

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Project: CRREL			Boring: CERCL12	Page: 3 of 5	
Depth/ Elevation (Ft.)	USCS Symbol/ Core Sketch	Soil/Rock Description	Sample Number & Depth	Blow Count & Recovery	Drilling Data
		SAND & Gravel (70% & 30%)			
22.5'		S5, 22.5 to 24.5', VF to Coarse SAND (80%) and rounded gravel (20%), trace silt 5Y 6/1	S5 2" 22.5' to 24.5'	12 23 29 31	Dry HNU=0ppm PID=0ppm 1059 5) Drove 2x 22.5'-24.5' 6) Drove 2x 27.5'-29.5' 7) Drove 2x 32.5'-34.5' 8) Drove 2x 37.5'-39.5'
24.5'			R=	1.2'	
27.5'		S6, 27.5' to 29.5', VF to Coarse SAND (95%) with subrounded Gravel (5%) Trace silt 5Y 6/1	S6 2" 27.5' to 29.5'	11 15 18 20	Dry HNU= 0ppm PID= 0ppm 1123
29.5'			R=	1.9'	
32.5'		S7, 32.5 to 34.5', VF to Coarse SAND (85%), Gravel (14%), 1% rounded Cobble, trace silt. 5Y 6/1	S7 2" 32.5' to 34.5'	17 17 24 25	Dry HNU=0ppm PID=0ppm 1133
34.5'			1.8'	R=1.8'	
37.5'		S8, 37.5' to 39.5', Same as above 5Y 6/1 Sand 60% Gravel 30% silt 10%	S8 2" 37.5' to 39.5'	9 16 32 20	Dry HNU=0ppm PID=0ppm 1142
39.5' 42.5'			R=1.9'	1.9'	

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BORING LOG GENERAL DATA
Borehole Number: CERCL12
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Depth/ Elevation (Ft.)	USCS Symbol/ Core Sketch	Soil/Rock Description	Sample Number & Depth	Blow Count & Recovery	Drilling Data
42.5'		S9 No Recovery	S9 2"	19, 13, 21, 26 R= 0.0'	1210 9) Drove 2X 42.5-44.5 (No sample recovered) 10) Drove 2X 47.5'-49.5' 11) Drove 2X 52.5-54.5' 12) Drove 2X 57.5-59.5'
44.5'					
47.5'		S10, 47.5' to 49.5', fine grained SAND, 90% Quartz, with trace silt, (<10%). 5Y 6/1	S10 2"	10, 11, 12, 12 R= 1.9'	Dry HNU = 0ppm PID = 0ppm 1229
49.5'					
52.5'		S11, 52.5' to 54.5' 52.5' to 53.5' VF to Med. grained SAND with 10% rounded gravel. 53.5' to 54.5', Very fine grained SAND (Quartz) 5Y 6/1	S11 2" 52.5' to 54.5'	12, 18, 21, 21 R= 2.0'	Dry HNU = 0ppm PID = 0ppm 1255
54.5'					
57.5'		S12, 57.5' to 59.5', fine grained Quartz SAND. 5Y 6/1	S12 2"	6, 14, 21, 21 R= 1.8'	DRY HNU = 0ppm PID = 0ppm 1352
59.5'					

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BORING LOG GENERAL DATA
Borehole Number: CERCL12
Page: 5 of 5
Signature: Robert R. Myers
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Depth/ Elevation (Ft.)	USCS Symbol/ Core Sketch	Soil/Rock Description	Sample Number & Depth	Blow Count & Recovery	Drilling Data
62.5'		Augered through rounded Gravel. S13, 62.5' to 64.5', broken cobbles of fine grained chlorite rich metamorphic rock. Dry	2", 62.5 to 64.5', S-13	100/.8 refusal	HNU=0ppm PID=0ppm 1408 No physical sample taken
64.5'		NOTE: Auger refusal @ 65' BGS, hole abandoned, switching to mud Rotary drilling, hole moved ~20', will con't sampling @ 67.5' BGS.		R= 0.8'	13) Drove 2X 62.5-64.5 (No sample Recovered)
		Bottom of Boring = 65' B.G.S. Original borehole abandoned after auger refusal @ 65' BGS. Hole collapsed to ~13' BGS as augers were removed. In the "new" CERCL12 location bedrock was encountered @ 62' BGS, the bedrock from 62' to 100' was phyllite of the Orfordville formation with interbedded Quartz rich chlorite.			14) Bottom of boring = 65' 15) boring abandoned 1/21/92 16) 6¼" hollow stem augers pulled prior to plugging 17) boring plugged with 24 bags of bentonite hole plug + 96 gallons of H_2O
100'		B.O.H @ 100' BGS. NOTE: Prior to permanent well installation the water level stabilized @ 85.2' BGS. Also: We lost mud circulation @ 81.5' BGS (large Fracture). Another Fracture was encounter @ ~97' BGS.			END 21 JAN 92. Drilled with mud rotary (5⅞" tri-cone) from 0' to 100', after which we set a 2" PVC temporary well which was air surged & bailed to determine if we had reached groundwater. Then we reamed the hole to 10" with a tri-cone bit and set the well after flushing out the drilling mud. END 25 JAN 92

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APPENDIX G: LABORATORY MEASUREMENTS OF HYDRAULIC CONDUCTIVITY AND WATER RETENTION IN LAKE SEDIMENTS ABOVE ESKER

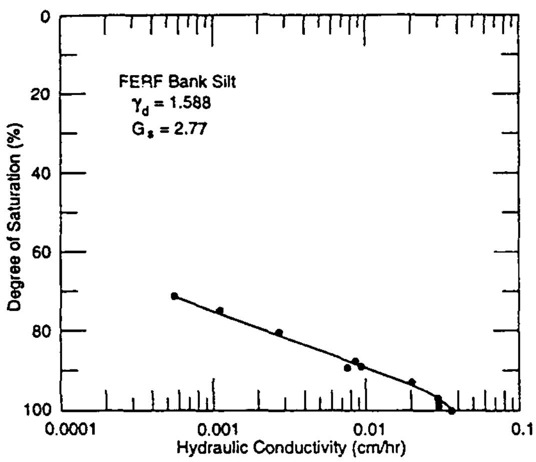

Figure G1. Hydraulic conductivity.

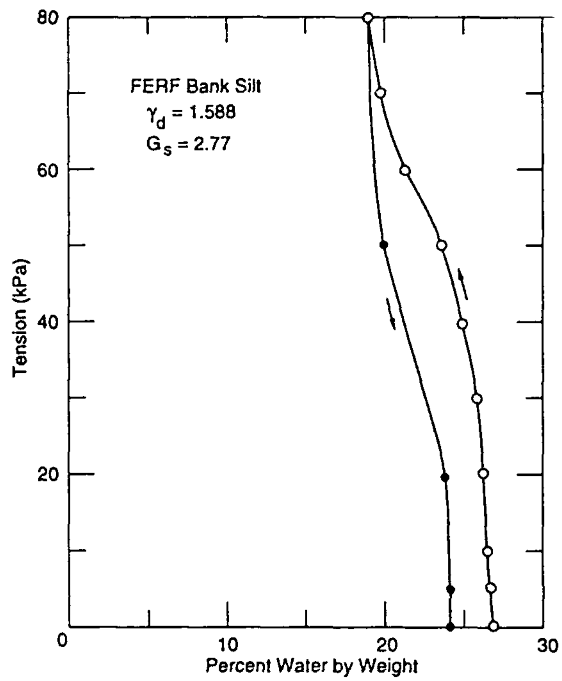

Figure G2. Water retention.

APPENDIX H: WATER QUALITY DATA FROM NORWICH, VERMONT, TOWN WELL AND CRREL
(Phase I Site Assessment)

Norwich town well

Table H1. Chemical analysis of water at site 1* (after Hodges et al. 1976).

Date: 3 February 1972 — Previous pumping: 2 days
Temperature: 6°C

Calcium	38	Fluoride	0.1
Magnesium	3.3	Nitrate	0.18
Sodium	2.1	Alkalinity as CaCo3	93
Potassium	1.9	Dissolved solids (sum)	129
Iron	0	Hardness (Ca and Mg)	108
Manganese	0	Hardness (noncarbonate)	15
Bicarbonate	144	Nitrate as N	0.04
Carbonate	0	pH	8.0
Sulfate	18	Silica	7.0
Chloride	2.8	Specific conductance (mhos at 25°C)	222

* All values except pH, specific conductance, and temperature in milligrams per liter.

Table H2. Summary of groundwater quality data (after Caswell et al. 1990).

	Concentration				
Parameter	*2 May 92*	*4 May 90*	*6 May 90*	*MCL*	*Units*
Turbidity	<0.1	<0.1	<0.1	1.0	Std units
Lead	<0.005	<0.005	<0.005	0.05	mg/L
Arsenic	<0.005	<0.005	<0.005	<0.05	mg/L
Cadmium	<0.002	<0.002	<0.002	0.01	mg/L
Barium	<0.10	<0.10	<0.10	1.0	mg/L
Nitrate	<0.50	<0.50	<0.50	10.0	mg/L
Mercury	<0.0005	<0.0005	<0.0005	0.0002	mg/L
Fluoride	<0.20	<0.20	<0.20	4.0	mg/L
Sodium	6	6	5	20.0	mg/L
Selenium	<0.005	<0.005	<0.005	0.01	mg/L
Silver	<0.005	<0.005	<0.005	<0.05	mg/L
Chromium	<0.011	<0.011	<0.011	0.05	mg/L
Foaming agents	<0.10	<0.10	<0.10	0.10	mg/L
pH	7.5	7.8	7.7	6.5–8.5	
Hardness	106	116	118		mg/L
Copper	<0.10	<0.10	<0.10	1.0	mg/L
Iron	<0.10	<0.10	<0.10	0.3	mg/L
Manganese	<0.010	<0.010	<0.010	0.05	mg/L
Zinc	<0.5	<0.5	<0.5	5.0	mg/L
Chloride	16	15	<15	250.0	mg/L
Coliform bacteria	*	<1		1	Col/100 mL
Volatile organics			n.d.		
Radon			760 ±70		pCi/L
Gross-alpha			–0.23 ±0.57		pCi/L

* Too numerous to count.
n.d.—none detected.

CRREL site

Table H3. USATHAMA water sample results, 19 March 1991 (after Ecology and Environment, in press).

Sample location	*Analytical method**	*MCL (ppb)*	*Compound*	*Frequency detected above MCL*	*Detected concentration (ppb)*
Organics					
New Hampshire outfall	UG05	5	Trichloroethylene	1/1	360
New Hampshire outfall	UM17	5	Trichloroethylene	1/1	236
Well CERCL #1 (32-1)	UG05	5	Trichloroethylene	1/1	930
Well CERCL #1	UM17	5	Trichloroethylene	1/1	849
Well CERCL #2 (32-2)	UG05	5	Trichloroethylene	1/1	220
Well CERCL #2	UM17	5	Trichloroethylene	1/1	142
Well CERCL #2	UM17	5	Tetrachloroethylene	1/1	18.2
Well CERCL #3 (32-3)	UM16	4†	Butylbenzyl phthalate	1/1	12.0
Well CERCL #3	UM17	N/A	Acetone	—	11.0
Well CERCL #4 (32-4)	UG05	5	Trichloroethylene	0/1	4.10
Well CERCL #4	UM17	5	Trichloroethylene	1/1	5.28
Well CERCL #5 (32-5)	UG05	5	Trichloroethylene	1/1	55
Well CERCL #5	UM17	5	Trichloroethylene	1/1	104
Ice well	UM17	5	Trichloroethylene	1/1	28,300
Ice well	UG05	5	Trichloroethylene	1/1	14,000
Ice well	UG05	5	Tetrachloroethylene	1/1	1,700
Ice well	UM16	5	Tetrachloroethylene	1/1	200
Ice well	UM16	5	2-Methylnapthalene	1/1	38
Ice well	UM16	—	4-Chloroaniline	—	13
Ice well	UM17	5	1,2-Dichloroethylene	1/1	149
Ice well	UM17	10**	1,2-Dimethylbenzene	1/1	200
Ice well	UM17	10**	1,3-Dimethylbenzene	1/1	100
Ice well	UM17	100	Chloroform	0/1	22.6
Ice well	UM17	5	Trimethylbenzene	1/1	500
Goodrich well (9-195)	UG05	5	Trichloroethylene	1/1	17
Inorganics					
New Hampshire outfall	99	5000	Barium	0/1	20.1
New Hampshire outfall	99	100	Chromium	0/1	4.78
New Hampshire outfall	99	300††	Iron	1/1	345
New Hampshire outfall	99	50††	Manganese	1/1	63
Well CERCL #1 (32-1)	99	5000	Barium	0/1	17.3
Well CERCL #1	99	1000††	Copper	0/1	16
Well CERCL #1	99	300††	Iron	1/1	421
Well CERCL #1	99	50††	Manganese	1/1	73
Well CERCL #2 (32-2)	99	1000††	Copper	0/1	12
Well CERCL #2	99	300††	Iron	1/1	380
Well CERCL #2	99	50††	Manganese	1/1	121
Well CERCL #3 (32-3)	99	5000	Barium	0/1	29.9
Well CERCL #3	99	100††	Copper	0/1	28.4
Well CERCL #3	99	300††	Iron	1/1	353
Well CERCL #3	99	50††	Manganese	1/1	90.8
Well CERCL #3	99	5000††	Zinc	0/1	94.7
Well CERCL #4 (32-4)	99	5000	Barium	0/1	25.2
Well CERCL #4	99	300††	Iron	1/1	720
Well CERCL #4	99	50††	Manganese	1/1	56.7
Well CERCL #4	99	5000††	Zinc	0/1	20.5
Well CERCL #5 (32-5)	99	5000	Barium	0/1	31.1
Well CERCL #5	99	100	Chromium	0/1	6.5
Well CECRL #5	99	1000††	Copper	0/1	25.6
Well CERCL #5	99	300††	Iron	1/1	760
Well CERCL #5	99	50††	Manganese	1/1	107
Ice well	99	N/A	Barium	N/A	8.1
Ice well	99	N/A	Copper	N/A	9.5
Ice well	99	N/A	Iron	N/A	2900
Ice well	99	N/A	Manganese	N/A	310
Ice well	99	N/A	Zinc	N/A	1400

Table H3 (cont'd).

Sample location	*Analytical method**	*MCL (ppb)*	*Compound*	*Frequency detected above MCL*	*Detected concentration (ppb)*
Goodrich well (9-195)	99	5000	Barium	0/1	47
Goodrich well	99	1000††	Copper	0/1	26.2
Goodrich well	99	300††	Iron	0/1	49.5
Goodrich well	99	50††	Manganese	1/1	79.3
Peacock well (9-50)	99	5000	Barium	0/1	67
Peacock well	99	1000††	Copper	0/1	36.1
Peacock well	99	300††	Iron	0/1	204
Peacock well	99	5000††	Zinc	0/1	410

* Analytical methods
UG05—halocarbons in H_2O by GC/CON
UM16—semivolatiles in H_2O by GC/MS
UM17—volatiles in H_2O by GC/MS
99—metals

† Proposed MCL for phthalates.

** Total xylenes.

†† Regulated secondary maximum contaminant levels (SMCL).

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Sally A. Shoop and Lawrence W. Gatto

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13. ABSTRACT (*Maximum 200 words*)

Trichloroethylene (TCE) was discovered in three of the industrial wells at CRREL, as well as in two domestic wells in bedrock across the river. This report describes the geohydrology of the CRREL vicinity and the subsurface behavior of TCE as part of the preliminary assessment of the CRREL site. There are three hydrologic units near CRREL—a high permeability esker deposit, lower permeability lake sediments and fractured bedrock. The esker is a high-yield sand aquifer paralleling the river that provides industrial water to CRREL from four wells. The pumping of these wells may induce groundwater recharge from the river. The lake deposits consist of fine-grained silt and sand with some clay, and these cover the esker deposit. These sediments lie above the fractured, folded and metamorphosed volcanics (schist and phyllite) of the Orfordville formation. The free surface water table shows very little hydraulic gradient and appears to be continuous through these units, indicating that they are hydraulically connected. TCE can migrate in the vapor phase, as a soluble component moving along with the groundwater, and as a separate or free phase. Small spills of TCE in the fine-grained soils at CRREL may not have exceeded the retention capacity of the soils and may remain within the soil pores, with a soluble component reaching the groundwater through infiltration. Larger spills may have passed through the saturated soil zone seeking bedrock lows, continuing their downward movement along bedrock fractures. Since the CRREL wells may induce recharge from the river, the possibility of the contamination coming from that direction should not be overlooked.

14. SUBJECT TERMS

Geohydrology	Groundwater	TCE
Geology	Groundwater pollution	
Hanover, N.H.	Pollution	

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